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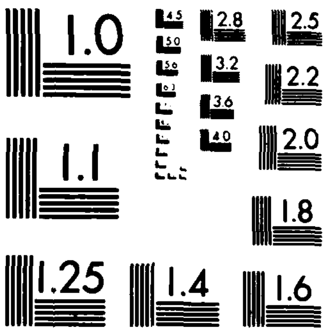
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Regional Variability of Thermohaline Finestructure

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ABSTRACT

Isopycnal variability of temperature is examined for the upper ocean on scales of several meters in the vertical and several hundred meters in the horizontal. A considerable number of rapidly sampled CTD profiles obtained in the Sargasso Sea (1979) and in the vicinity of the Faeroe Islands north of Scotland (1980) are described. Analyses of fine-scale variability within, adjacent to and away from a strong front are compared. A number of small, intense features are revealed which would likely have been missed by conventional sampling procedures. Analysis of strong interleaving in a frontal regime supports the hypothesis that salt-fingers drive thermohaline intrusions.

ACKNOWLEDGMENTS

The data presented in this report were acquired by the Physical Oceanography Branch of the Naval Oceanographic Office (NOO) in response to requirements of the Ocean Measurements Program. NOO was also responsible for the data processing and for the publication of valuable data summaries which include extensive graphics.

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REGIONAL VARIABILITY

OF THERMOHALINE FINESTRUCTURE

I. INTRODUCTION

Small-scale variability of temperature, salinity, and density in the upper ocean is important to Navy interests for several reasons. First, the propagation speed of sound waves depends on the compressibility of water which, in turn, depends primarily on temperature. Second, a controlling factor for internal waves is the Brunt-Vaisala frequency which depends on the density distribution; static and dynamic stability depend on density as well. Third, the distributions of property gradients provide a medium for the observation of various phenomena. The fields of temperature, salinity and density fluctuate on many time and space scales about some perceived "mean" state. Clearly, a better knowledge of distributions and scales of fluctuations will enhance our understanding of the oceanic environment.

There are a number of contributing factors to oceanic variability on these scales: the straining of gradients by internal waves; vertical mixing events associated with convection, breaking internal waves, or vertical shear instabilities; instabilities and turbulent mixing associated with horizontal current shears; interleaving of different water masses in and around thermohaline fronts; and water type modification associated with surface fluxes of heat and salt. The variability produced by these processes falls into two broad categories: variations in temperature (and salinity) that cause density variations, and variations in temperature accompanied by density-compensating variations in salinity. Small-scale variability in a given area may be predominantly in one or the other of these categories or may contain comparable levels of both. Processes in one category can interact with processes in the other through diffusion, convection, and mixing.

On a temperature-salinity (T-S) diagram, uncompensated variability is characterized by tight clustering of points, forming a single, relatively smooth curve. Spatial structure is manifested through the distribution of the vertical coordinate along the curve. The vertical straining of gradients by internal waves, and density step structures fall into this category. Vertical temperature and salinity profiles are representative of the density profile.

Density-compensated variability, on the other hand, is characterized by a scattering of points in the T-S domain. Vertical profiles of temperature and salinity may be highly structured while that of density is smooth. Adjacent profiles

of temperature (and salinity) may be offset while the corresponding density profiles are coincident. This vertical and horizontal "isopycnal" variability reflect thermohaline finestructure and frontal structure, respectively. Combined, they constitute evidence of thermohaline intrusions.

The level of variability depends quite strongly on the proximity of mesoscale features such as fronts and strong current shears. Different atmospheric conditions are likely to have an effect as well. In this study, six sets of rapidly sampled sections of temperature and salinity, from different oceanographic environments, are compared showing systematic differences in the level and character of fine-scale activity, on scales of 200 m to 4 km horizontally and tens of meters vertically. Since such scales are difficult to resolve using standard observational methods, special sampling techniques were employed.

II. DESCRIPTION OF DATA

The data described in this paper were acquired during two surveys conducted by the Naval Oceanographic Office (NOO) aboard USNS KANE. One survey was carried out in the fall of 1979, in the Sargasso Sea about 500 nm east of Jacksonville, Florida. The other was conducted in the northeast Atlantic Ocean and southern Norwegian Sea in Fall, 1980. These surveys included current measurements, sea water chemistry and CTD (Conductivity-Temperature-Depth) profiling.

CTD data were acquired with a Neil Brown Mark III instrument. Sampling consisted primarily of sections of deep, single casts (profiles) and groups of shallow, "yo-yo" casts (multiple-profile) at selected locations. The present study focuses on one yo-yo station from the Sargasso Sea survey (Fig. 1) and five yo-yo stations from the Norwegian Sea area (Fig. 2). Positions of stations are given in Table 1.

Each of the six yo-yo stations* discussed consisted of from four to seven casts, extending over a period of from 24 to 36 hours. Each cast lasted about 2.5 hours and consisted of about 22 CTD profiles extending from the mixed layer to about 250 meters in depth; the instrument was raised and lowered between fixed depths continuously throughout a cast with about six minutes between successive down profiles (only down

*Each individual cast is identified by a two-part number, SSSCCC, where SSS is the "station number" and signifies a general geographic location, and CCC is the "consecutive cast number" which is unique and independent of SSS. Stations may be referred to by only SSS when a particular cast is not under consideration; when casts are discussed, the entire number is used.

profiles were used in the analysis). A new cast was begun every four hours following ship repositioning to avoid tidal and inertial aliasing. An example of temperature profiles and T-S diagrams is shown in Figure 3.

At the beginning and end of a series of yo-yo casts, water samples were collected in order to check CTD salinities. Values stayed within 5 parts per million which is adequate for finestructure analysis.

Navigation was primarily by LORAN-C with checks by satellite fixes. During each cast the ship drifted from two to four kilometers as a result of currents and wind, the latter usually being the dominant factor. Consequently, each cast constituted a short, horizontal section rather than a true Eulerian time-series. In most cases, fixes were obtained every 15 minutes. Plots of the fixes implied that the sections were relatively straight lines although drift speeds varied slightly.

Expendable current profile (XCP) measurements were made between successive casts at several yo-yo stations in the Norwegian Sea area. These were analyzed and reported by Burns and Lombard (1982).

CTD data were recorded on computer-compatible magnetic tape. Some preliminary analysis was done aboard ship, but the bulk of the data processing was done on the NOO UNIVAC 1100 computer following the cruises. Processing included the application of matching filters to temperature and conductivity, conversion to one decibar pressure resolution and computation of salinity and density. Plots of all survey data can be found in the exhaustive data summaries prepared by NOO for each of these cruises (Teague, 1981). Details of CTD data processing software procedures are described by Hallock (1982).

III. ANALYSIS

In strong thermohaline fronts, intrusive features are usually obvious in temperature sections. On the other hand, relatively weak T-S anomalies can be masked by vertical displacements associated with dynamic processes such as internal waves and mesoscale currents. Hence, it is useful to separate these effects so that T-S anomalies can be examined in isolation. To achieve this separation the following analysis was undertaken on the CTD yo-yo data. A quantity defined as isopycnal temperature anomaly (T') is derived as follows:

For an ensemble of vertical profiles of T(Z), S(Z) and $\sigma_t(Z)$, averages of T and S are calculated as functions of σ_t.

$$\overline{T}(\sigma_t) = \frac{1}{N}\sum_{i=1}^{N} T_i[Z(\sigma_t)]$$

i represents profile sequence no.

$$\overline{S}(\sigma_t) = \frac{1}{N}\sum_{i=1}^{N} S_i[Z(\sigma_t)]$$

The anomaly for each profile is then computed:

$$T_i'[Z(\sigma_t)] = T_i[Z(\sigma_t)] - \overline{T}(\sigma_t)$$

$$S_i'[Z(\sigma_t)] = S_i[Z(\sigma_t)] - \overline{S}(\sigma_t)$$

Root mean square (rms) of the anomalies are then calculated:

$$\delta_T(\sigma_t) = \{\frac{1}{N}\sum_{i=1}^{N} (T_i'[Z(\sigma_t)])^2\}^{\frac{1}{2}}$$

$$\delta_S(\sigma_t) = \{\frac{1}{N}\sum_{i=1}^{N} (S_i'[Z(\sigma_t)])^2\}^{\frac{1}{2}}$$

again, functions of σ_t.

Each of the six yo-yo CTD stations described in Section II was taken to be an ensemble of profiles. An average T-S relation was computed for each. Plots of these averages with rms envelopes are presented in Figures 4-9. The plotted curves are:

$\overline{T}$ vs. $\overline{S}$

$\overline{T} - \delta_T$ vs. $\overline{S} - \delta_S$

$\overline{T} + \delta_T$ vs. $\overline{S} + \delta_S$

The envelopes are interpreted as variation along lines of constant σ_t. Figure 9 shows all average Norwegian Sea curves together, on the same scale to emphasize differences between regions.

Typically, one station (ensemble) consisted of about 180 profiles grouped into 7 casts. For each cast, vertical sections of T' and σ_t were plotted together. These sections comprise the bulk of the presentations beginning with Figure 11. The sections are represented as functions of time but are better interpreted as functions of horizontal distance, as previously stated.

A few cautionary notes are in order. In the section plots features with horizontal scales less than about 10 minutes

(0.1 km) are likely to be sampling noise or computational artifacts and should be ignored. Changes in slope of isopleths on short scales could be partially due to changes in drift velocity through a feature with a constant horizontal gradient. Aliasing of high-frequency internal waves is inevitable: this aspect will be discussed further in Section IV. Time scales of intrusive features, however, are likely to be longer than cast durations and should be reasonably well resolved.

IV. DISCUSSION

A. REGIONAL VARIABILITY

Average T-S diagrams for the Sargasso Sea data (Fig. 4) and for the Norwegian Sea data (Figs. 5-10) show differences are most apparent in Figures 4 and 10 where data are plotted on similar scales.

Since the yo-yo casts were confined to the upper 250 m, the average T-S curves extend only to a limited degree into the deeper water masses present. Furthermore, this extent is variable, since the mean vertical density structure varies from station to station. The limited vertical range was necessary, however, to obtain high horizontal resolution.

The Sargasso Sea (Fig. 4) station shows the two levels of enhanced isopycnal variability located above and just below the seasonal pycnocline. The near surface variability is likely to be related to diurnal heating and to precipitation events which were present during the experiment. Below the pycnocline, the isopycnal variability may have been related to frontal processes in the area as reported by Katz (1969). There was some evidence for the presence of a weak front a short time before the Sargasso Sea yo-yo data were acquired (Hallock, et al., 1982).

The regions in the vicinity of the Iceland-Faeroe-Shetland gaps are oceanographically complex. The Northeast Atlantic Current, which is part of the Gulf Stream system, divides south of the Faeroe Islands, flowing northwestward along the south coast of Iceland as the Irminger Current, and northeastward through the Faeroe-Shetland gap into the Norwegian Sea, converging with the Norwegian coastal current and the East Icelandic Current (Sverdrup, Johnson and Flemming, 1942). Between Iceland and the Faeroe Islands lies a region characterized by an intense thermohaline and density front which is crenellated with eddies and meanders (Hansen and Meincke, 1979). This frontal region also lies between the Northwestward Irminger Current and the Southeastward East Icelandic Current. Station 109 (Fig. 5), which was about 150 nm southwest of the front, shows the least isopycnal variability and consists primarily of North Atlantic water in the range of the data. Stations 171 and 175 (Figs. 7 and 8), which

were 10-100 km north of the front, show more variability but still have relatively tight T-S correlations. These curves imply varying degrees of mixing of East Icelandic Current and North Atlantic water near the surface. Station 117 (Fig. 6), which was in the front, shows a high level of isopycnal variability. Only at the deepest points in the casts does the T-S relation tighten. Station 117 displays active mixing of North Atlantic water, East Icelandic Current water and North Icelandic/Arctic Intermediate water. Mixing in and near the front involves intrusive interleaving and meandering, along front flows and mesoscale eddies (Steele, 1967; Hansen and Meincke, 1979). Station 180 (Fig. 9) was relatively inactive below 50 m. Near the surface, however, fresher Norwegian coastal water is evident mixing with North Atlantic water. A sharp pycnocline results from the overlying fresh water.

While the positions and shapes of the average T-S curves vary considerably from station to station, the isopycnal variability envelopes are similar and the implied variance small except at Station 117 and near the surface at Station 180. Finally, since the average T-S curves are relatively unstructured in the vertical, it can be inferred that most density-compensated small-scale vertical structures are also isopycnal anomalies in the horizontal.

B. LOCAL SPACE-TIME SCALES

During each cast the ship was observed to drift relative to the water, as well as over the ground so the resulting sections are functions of horizontal distance as well as of time. Since some structures are seen to repeat in successive casts (sections), the spatial interpretation appears more favorable. There is still a space-time ambiguity, and certain features such as internal waves with periods less than two hours cannot be adequately resolved. Intrusive features, however, are likely to have considerably longer time scales. Following Toole and Georgi (1981) an estimate of the minimum time-scale of an intrusive event can be obtained from:

$$T \sim 1/A_S m^2$$

where

A_S = 10 cm^2/sec is the effective diffusivity of salt due to vertical salt fingering,

and $\frac{2\pi}{m} = D \approx 50$ m (5000 cm) the vertical thickness of the intrusion (from Fig. 25).

This leads to a time scale of about 17 hours.

Hence, a section obtained over a period of 2.5 hours gives a quite synoptic representation of the intrusion field. Consequently, the vertical section contours of isopycnal temperature anomaly can be interpreted as functions of depth and horizontal distance. If high-frequency internal waves are present, some aliased distortions of isolines may result, but general characteristics of intrusions will not be disturbed. Also, interactions between internal waves and intrusions tend to be minimal at frequencies above inertial (Toole, and Georgi 1981).

A further consideration is vertical current shear. During much of the experiment, expendable current profilers (XCP) were launched. Data from these were analyzed (Burns and Lombard, 1982) and show vertical current shear of 2.5×10^{-3} - 5×10^{-3} sec^{-1} away from the front and up to 10^{-2} sec^{-1} in the front. Actual current speed changes were of the order of 10-20 cm/sec over depth intervals of 20 m. Maximum shear was found between 150 and 200 m. Ship drift speeds were of the same order; hence, some contamination of information was inevitable. Since XCP velocities are relative to an unknown constant, a quantitative assessment of this contamination is not possible at present. On the other hand, if it is assumed that the most energetic component of the flow is inertial, since the yo-yo stations extended over at least one inertial period, contamination of the average T-S relations is likely to be minimal.

C. SPATIAL CHARACTERISTICS

At Station 26 in the Sargasso Sea there were weak but well-defined tongues in and near the seasonal thermocline (Figs. 11-17). There were weaker layers below in the 18° water. In cast 26086 (Fig. 16) there was a strong negative anomaly near the surface accompanied by a depression of isopycnals. This anomaly may have been the result of a precipitation event. The tongue-like features, such as those evident in casts 26081-26084 (Figs. 11-14), may be related to frontal processes in the area.

Station 109, located southwest of the Faeroe Islands, again exhibited weak intrusive activity (Figs. 18-24), but the structure was quite different. The thermocline was weaker and intrusive patches rather than tongues were present. Cast 109-083 (Fig. 24) crossed a weak front. The features at 109 are likely to have been fragments of intrusions being advected in the frontal area about 100 nm to the northeast, which were advected southward in a manner similar to that suggested by Toole (1981). To a large extent the intrusive features appear to have been uncorrelated with variations in the density field. There were exceptions, however, such as the large positive patch above the thermocline in Cast 109-081 (Fig. 22), which was associated with a region of weak density stratification.

By far, the strongest isopycnal variability was found at Station 117, which was located in the Iceland-Faeroe oceanic front. The station position was chosen by locating a well-defined section of the front on horizontal maps of temperature prepared from AXBT data (see Fig. 7, Hallock, 1981). A study of navigation data revealed that casts 117-092 to 117-095 were oriented roughly across-front, while the remainder were oriented along-front. Due to uncertainties in ship movement relative to the water, in which significant currents were most likely present, these assumed orientations must be interpreted with caution. The plot of cast 117-092 (Fig. 25) shows the most striking evidence of cross-frontal interleaving. The downward slope of isopycnals (northeast-southwest) is consistent with this interpretation.

The contours of isopycnal anomaly show two warm, saline tongues from the south interleaving with two cool, fresh tongues from the north. Examination of vertical derivatives of temperature and salinity for this cast reveal conditions favorable for salt finger convection at several locations above the cool tongues. The cool tongues appear to cross isopycnals downward and the warm tongues upward. This observation is consistent with the dynamics of salt-finger-driven intereaving neglecting geostrophic effects (as in laboratory experiments reported by Turner, 1978).

However, the association of salt fingering with the sense in which intrusions cross isopycnals in a rotating system is more complex, and the along-front tilt of the intrusion is likely to be the controlling factor (Posmentier and Hibbard, 1982). Similar features appear in plots of Casts 117-093, 117-094 (Figs. 26 and 27) although not as pronounced as in 117-092. In Cast 117-094, the slope of the isopycnals was somewhat ambiguous; the orientation of the section relative to the front is uncertain. Cast 95 (Fig. 22) again shows features of the intensity of Cast 117-092. Isopycnal slopes indicate that only the first two-thirds of the section were cross-frontal. It is likely that Casts 117-092 and 117-095 represent sections through the same feature at slightly different angles or positions. Casts 117-096 through 117-098 (Figs. 29-31) were oriented essentially along-front. Intrusions take on a more layered appearance in these casts, and isopycnals are quite horizontal.

Station 171 (Figures 32-35) was located about 180 nm northeast of the front. The intrusive field was similar to that at 109 in anomaly magnitudes but compressed vertically, consistent with the stronger pycnocline. The strongest isopycnal anomalies appear just below the pycnocline, analogous to those at Station 26 in the Sargasso Sea. Ship drift was primarily northward at this station. A major difference between Stations 171 and 26 is that the former exhibits significantly shorter horizontal scales of intrusive patches and more intense activity below the pycnocline. This should not be surprising, however, since the Southern Norwegian Sea is a major mixing area for several water masses.

At Station 175 (Figs. 36-41) patterns similar to those at Station 109 were found. Station 175 was probably more in line with the inflow of North Atlantic surface water (see Fig. 10) through the Faeroe-Shetland Channel. Ship drift at Station 175 was northwestward. Of particular interest is the deep frontal feature evident in Cast 175-156 (Fig. 36). This feature is likely to have been associated with the Norwegian front. Intrusive activity for Casts 175-157 and 175-159 was relatively weak. For Casts 175-159 through 175-161, some definite cool tongues intruding from the north were present between 100-170 m.

Station 180 (Figs. 42-45) was located about 100 nm off the Norwegian coast. The upper 40 m was dominated by fresh coastal water that formed a strong pycnocline. Ship drift was predominantly toward the southeast; hence, the isopycnal slope is indicative of a southwestward component of geostrophic flow. The station location was near the historical confluence of the Norwegian Current and the North Atlantic Current which both flow northeastward at this point. Hydrographic sections in an atlas of historical data from the Norwegian Sea being prepared by Saunders (in preparation) show persistent countercurrent or eddy-like features consistent with Station 180. The profiles were too shallow to obtain a quantitative estimate of the current, but since there was a 20-40 knot southerly wind throughout the station, and the drift was southward against the wind, a rather strong southward flow is implied. There was a considerable amount of isopycnal temperature anomaly in and above the pycnocline that is clearly a result of the surface water intrusion. The most interesting feature, however, was a lens of relatively warm, saline water and reduced stability at a depth of about 80 m apparent in Casts 180-168, 180-169. The dynamical significance is not clear, but the lens might have been rotating as suggested by Dugan et al. (1982). The positive tongue in Casts 180-170, 180-171 may have been part of the lens as well, but this cannot be verified. Finally, Cast 180-171 displays a negative anomaly intruding from the southeast which might be part of the Norwegian Front.

In summary, the results presented exhibit a variety of small-scale intrusive features. This analysis constitutes a pilot representation and by no means exhaustive study of such features. Statistics on such data as these must be interpreted with caution due to existence of submesoscale phenomena which appear in some casts but not in others. The analysis also points out that features, such as the lens found at Station 180, are small enough to be missed or certainly aliased in a traditional hydrographic section. The so-called mixed layer may contain pronounced horizontal gradients of temperature and salinity while being relatively homogeneous in density. There may also be small-scale, short-lived density structure in the mixing layer, such as the lens in Sargasso Sea Cast 26086.

This approach provides a method of characterizing the small-scale intrusive background in an area. Once average conditions have been determined, individual profiles acquired at some future time could be compared with the area statistics and classified.

V. RECOMMENDATIONS FOR FUTURE WORK

Examination of sections of isopycnal temperature anomaly is interesting but can become cumbersome when many data sets must be reviewed. More concise methods for summarizing individual casts as well as better statistics for each station are being developed.

Future observational work should include better current measurements to provide advection information. Simultaneous profiles of current velocity relative to the ship would be ideal for this and is practical with the VCTD profiler developed at NORDA by Perkins and Saunders (1980). The inclusion of current meter moorings in the vicinity of CTD measurements would greatly enhance the interpretation of results as well. Longer sections with more positive control over locations of individual profiles are required, with efforts to track particular features. Near-surface current structure could be monitored with radar-tracked drogues.

The technique is not restricted to the smallest scales. It can be applied to sets of deeper profiles. Of particular interest in this regard are the extensive cross-front CTD sections obtained in 1980 and 1981 in the Iceland-Faeroe-Norwegian Front area. Plans for FY 83 include analysis of such data.

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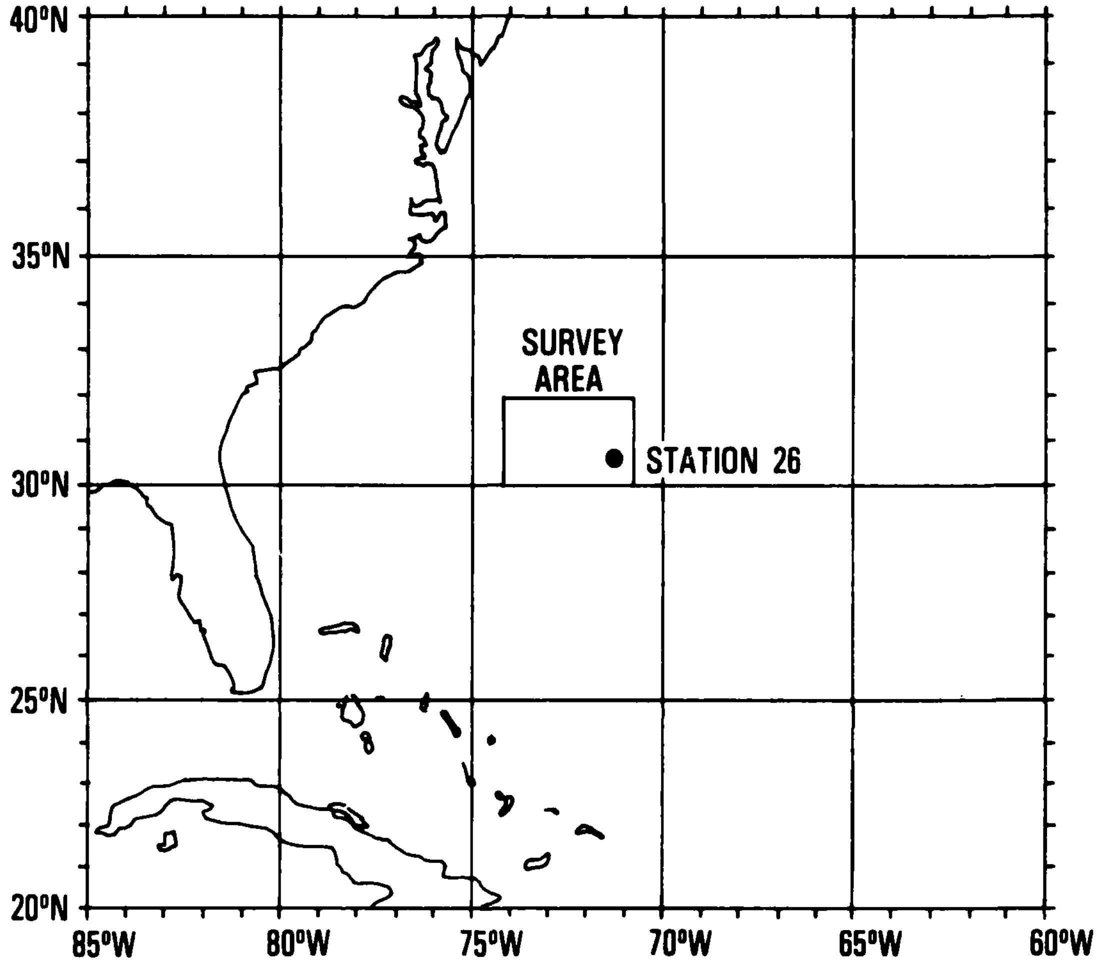


Figure I. Site of the 1979 survey: Sargasso Sea (USNS KANE cruise 34918--Phase II).

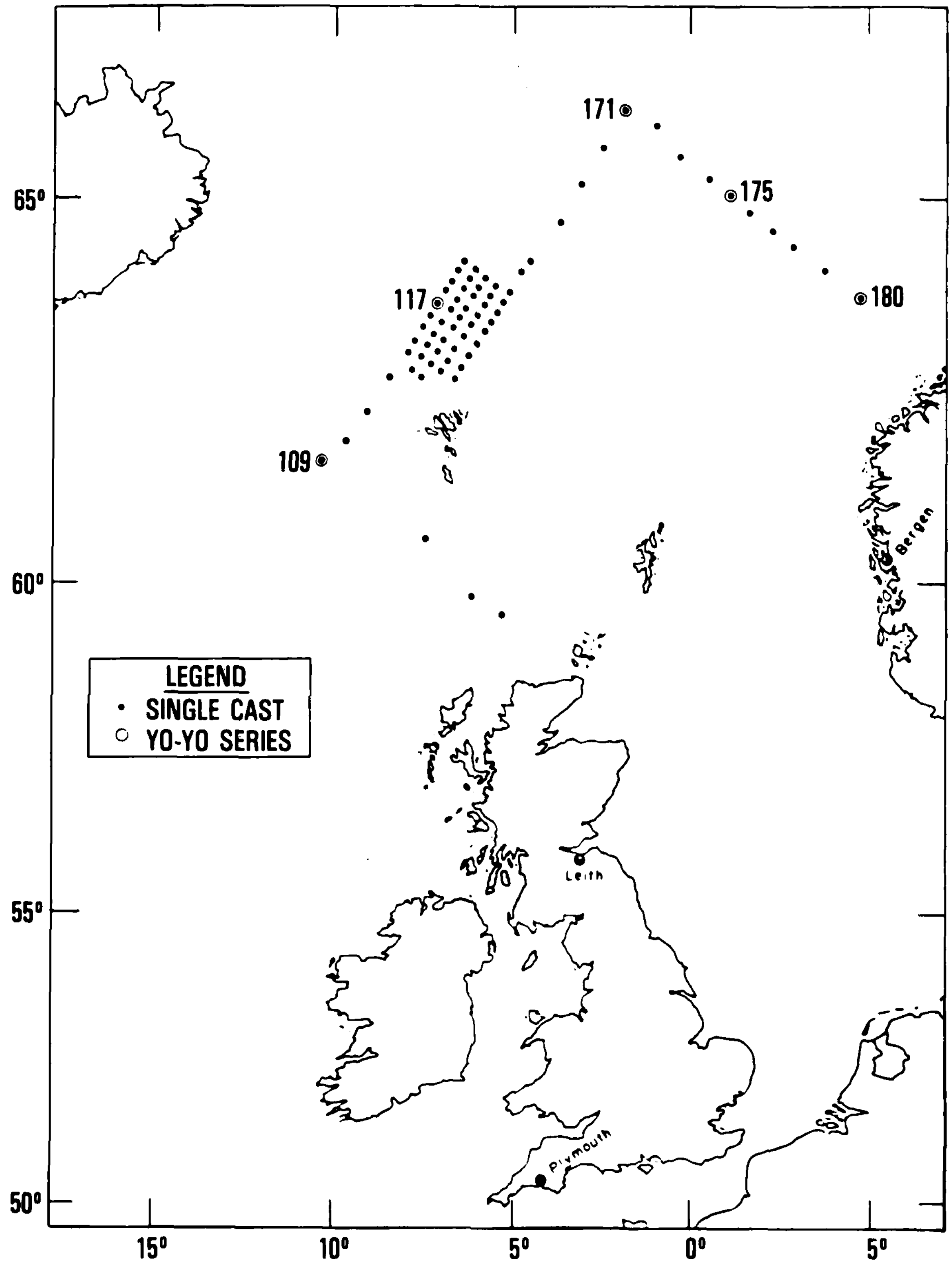
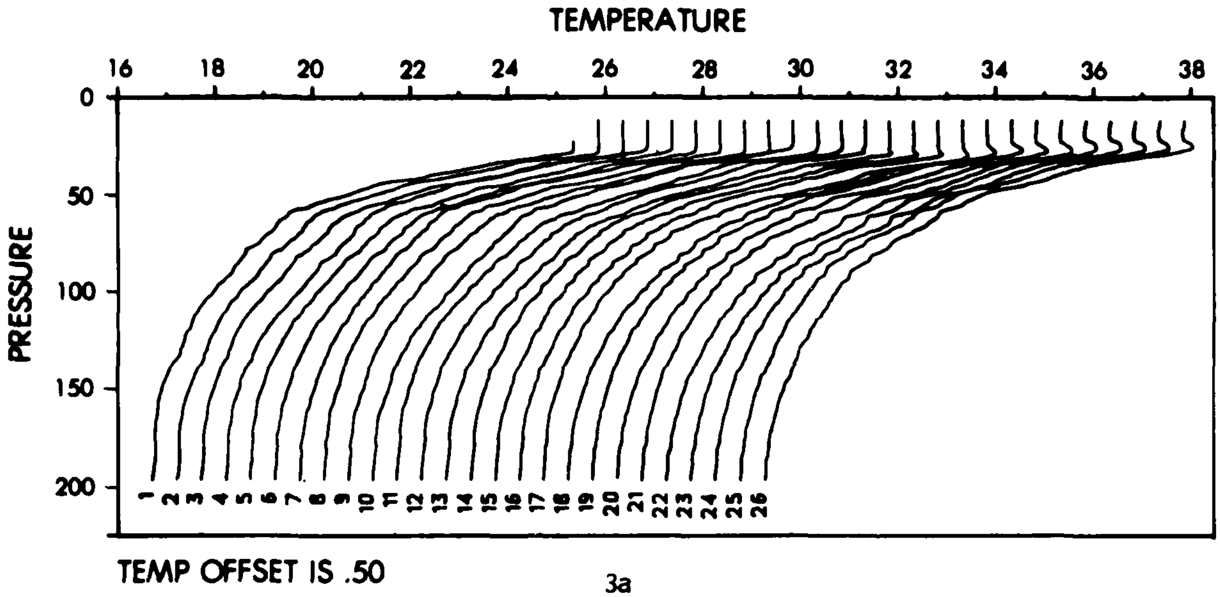


Figure 2. Site of the 1980 survey: Northeast Atlantic Ocean and Norwegian Sea (USNS KANE cruise 270980--Phase II).



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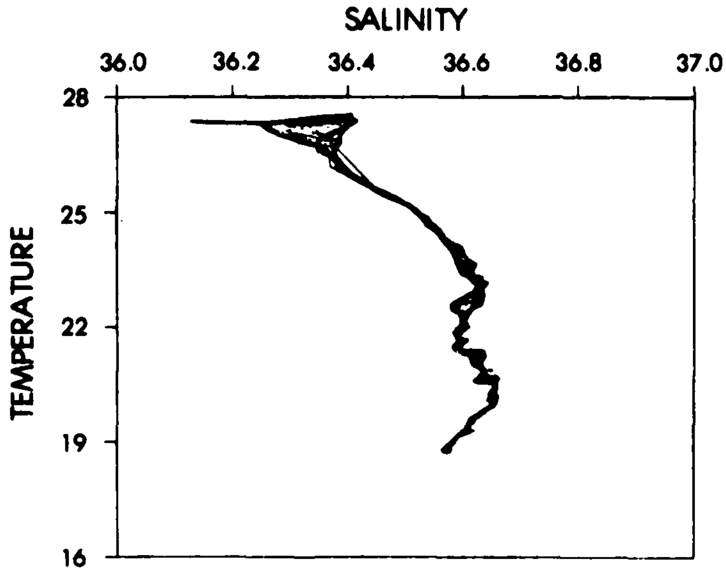

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Figure 3. Example of temperature profiles and temperature-salinity diagrams (Sargasso Sea Station 26083).

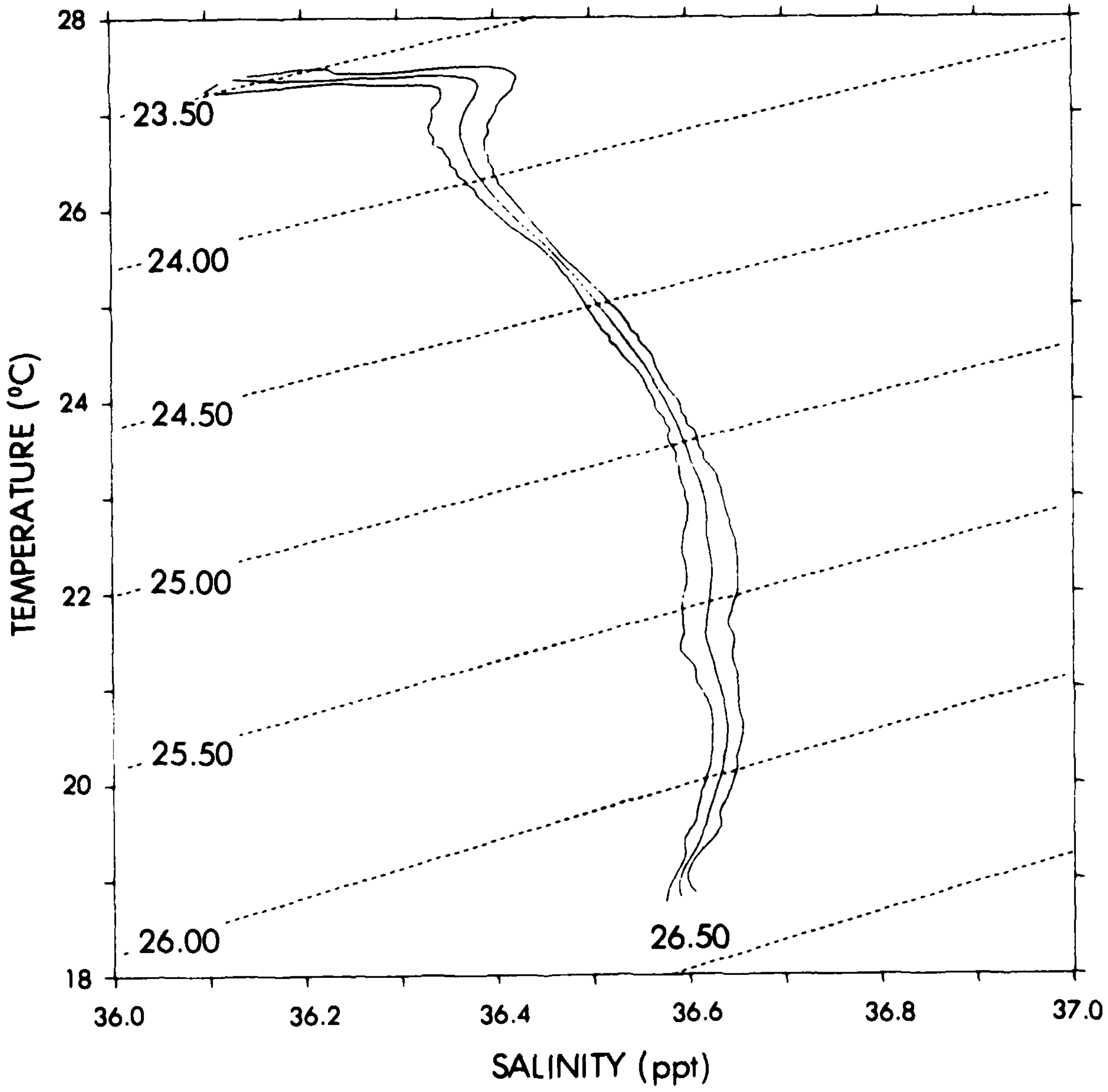

Figure 4. Average temperature-salinity relation, with root-mean-square (rms) deviation envelope, for Sargasso yo-yo CTD Station 26 (means and deviations computed on isopycnic surfaces).

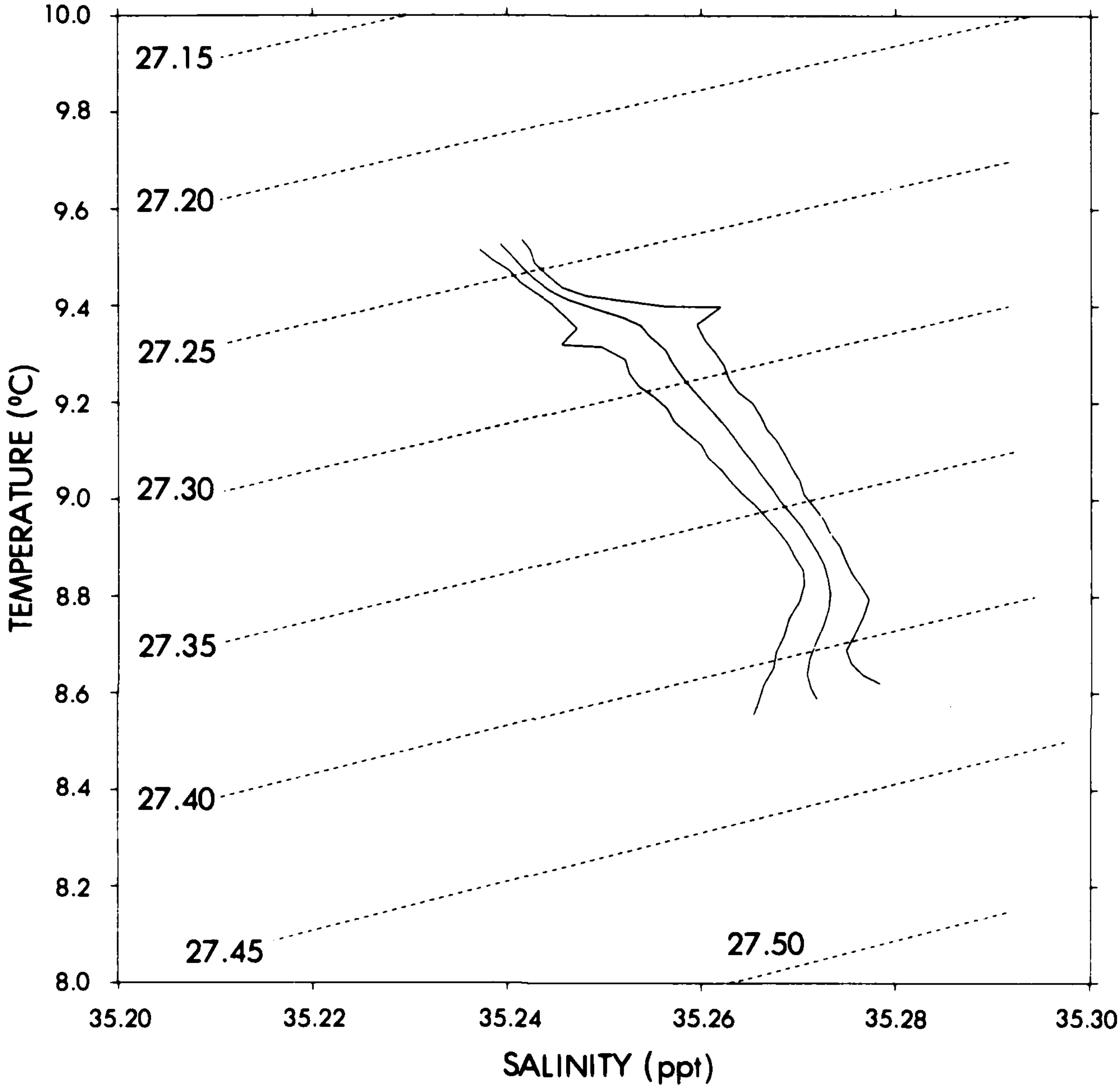

Figure 5. Average temperature-salinity relation with rms deviation envelope, for Norwegian Sea yo-yo CTD Station 109 (means and deviations computed on isopycnic surfaces).

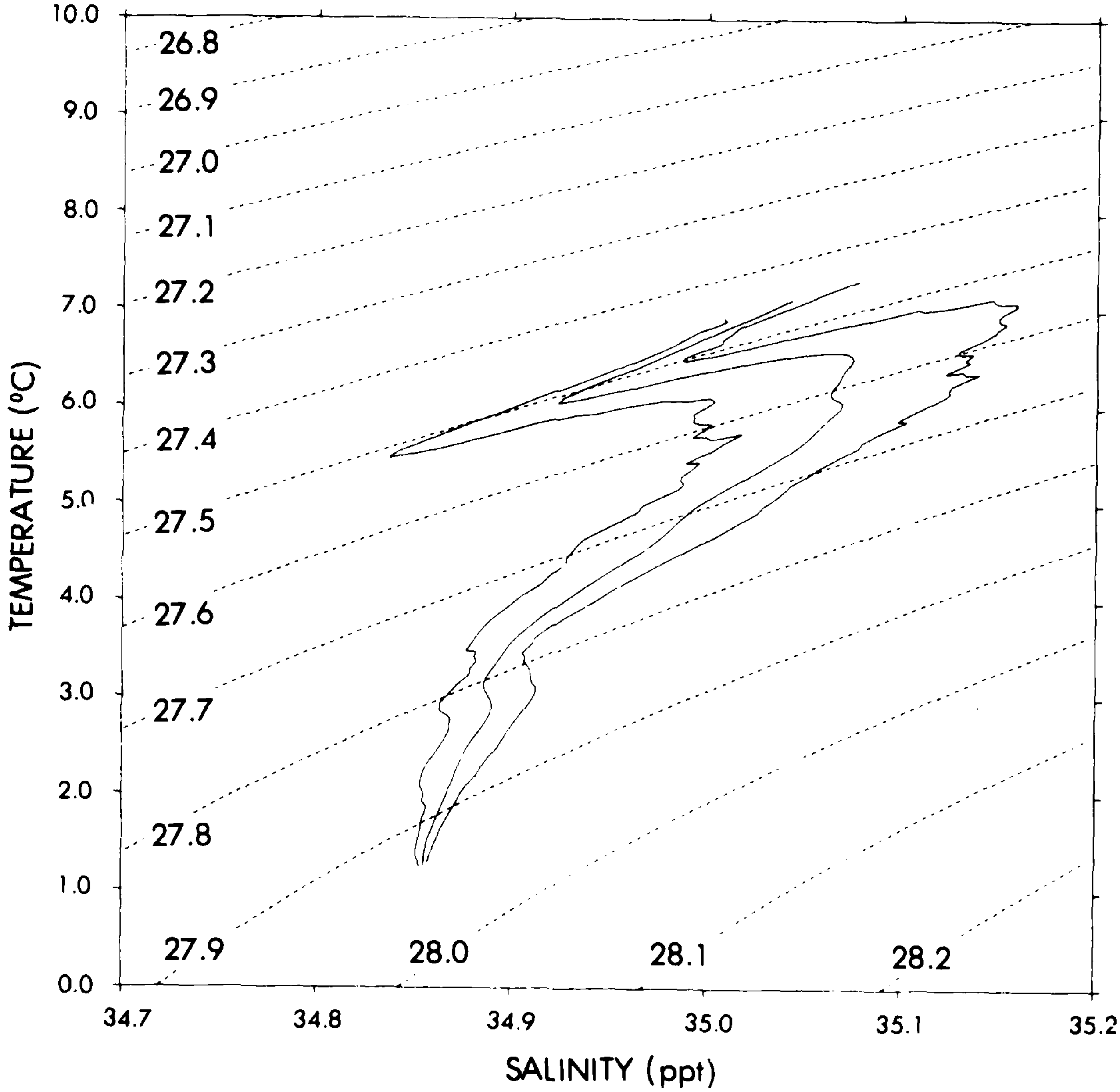

Figure 6. Average temperature-salinity relation, with rms deviation envelope, for Norwegian Sea yo-yo CTD Station 117 (means and deviations computed on isopycnic surfaces).

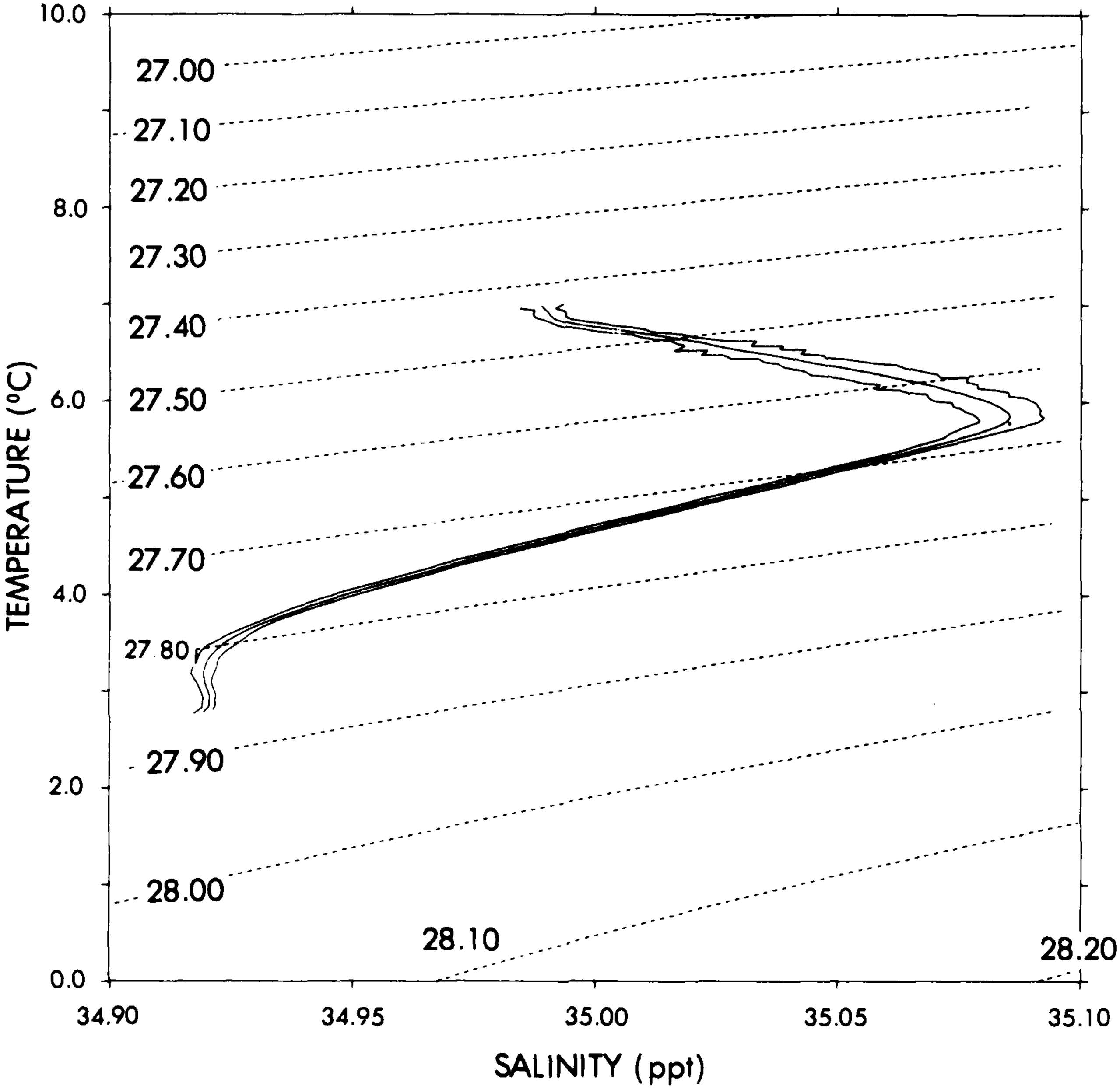

Figure 7. Average temperature-salinity relation, with rms deviation envelope, for Norwegian Sea yo-yo CTD Station 171 (means and deviations computed on isopycnic surfaces).

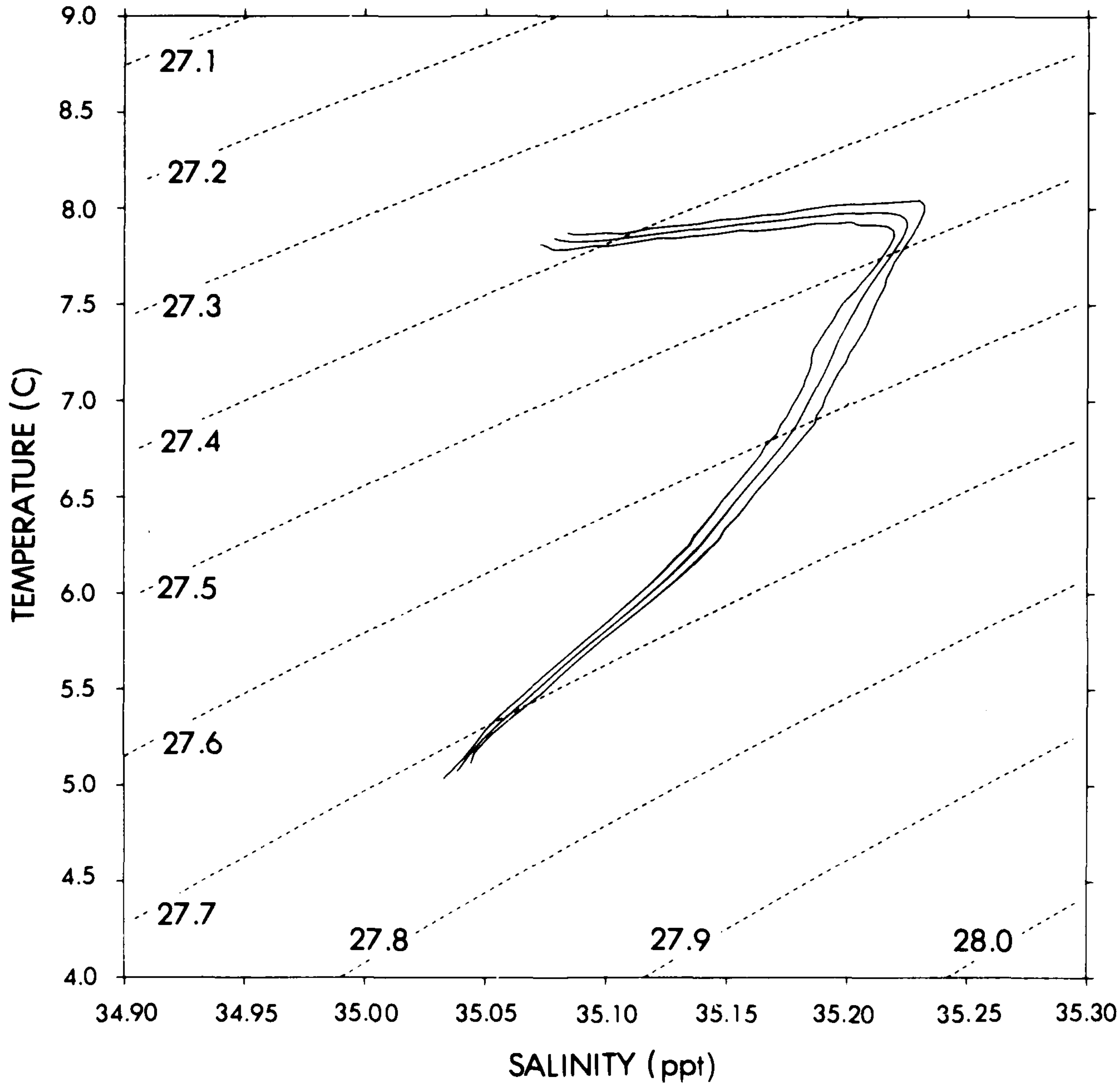

Figure 8. Average temperature-salinity relation, with rms deviation envelope, for Norwegian Sea yo-yo CTD Station 175 (means and deviations computed on isopycnic surfaces.)

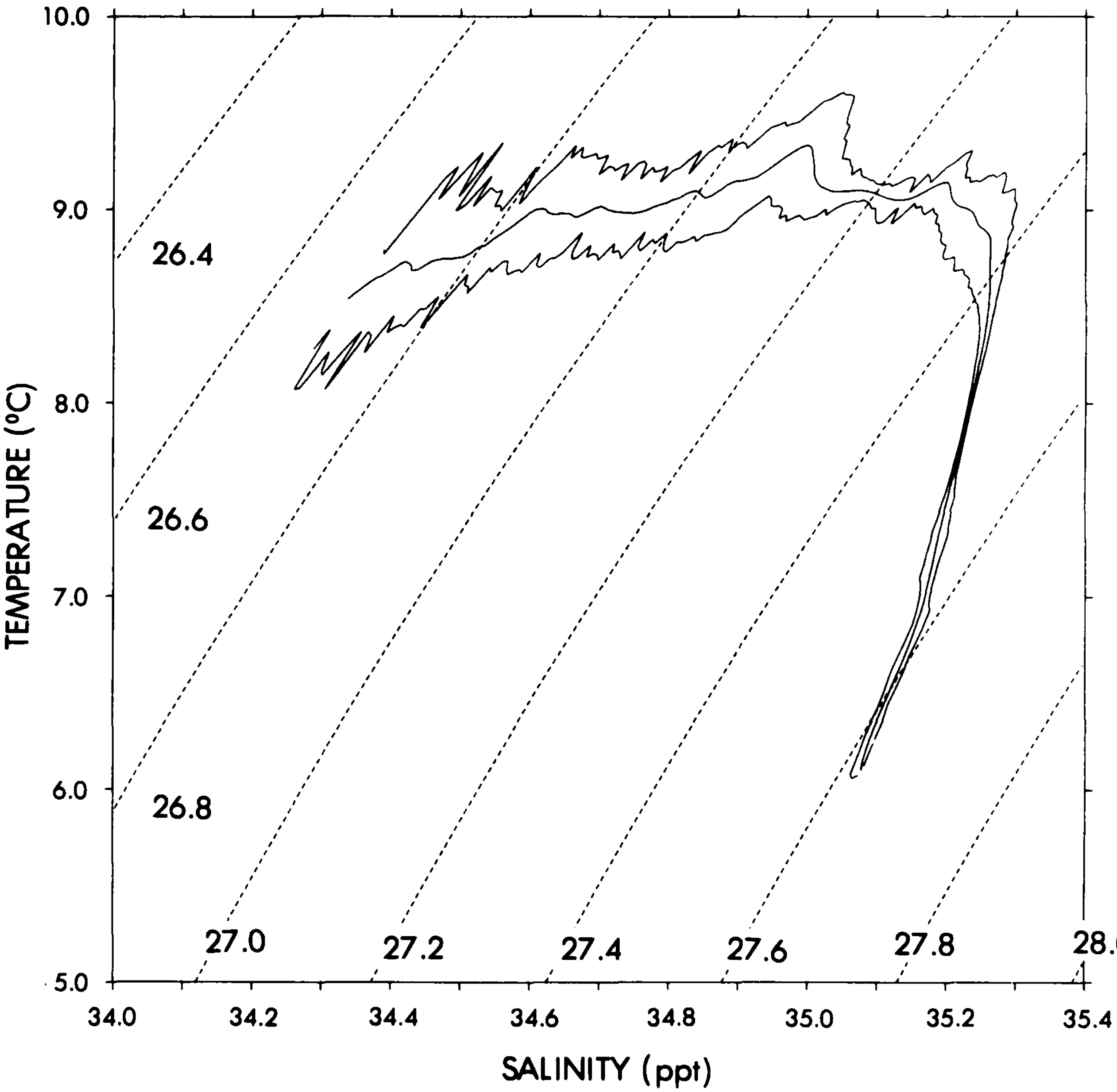

Figure 9. Average temperature-salinity relation, with rms deviation envelope for Norwegian Sea yo-yo CTD Station 180 (means and deviations computed on isopycnic surfaces).

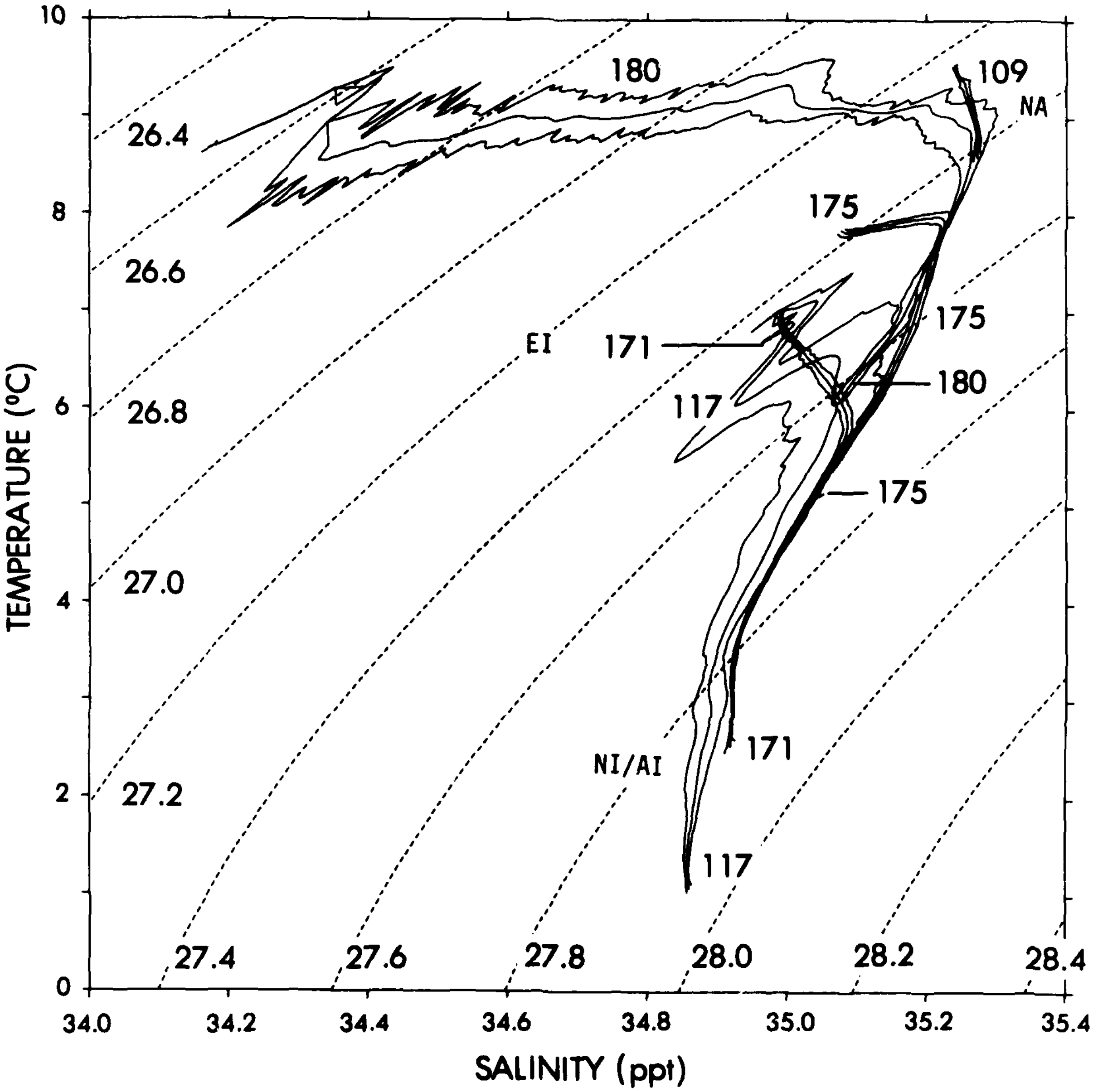

Figure 10. Combined average temperature-salinity relations for Norwegian Sea yo-yo CTD stations 109, 117, 171, 175, 180. Water types indicated on diagram are: NA-North Atlantic water; NI/AI-North Icelandic/Artic Intermediate water; EI-East Icelandic Current.

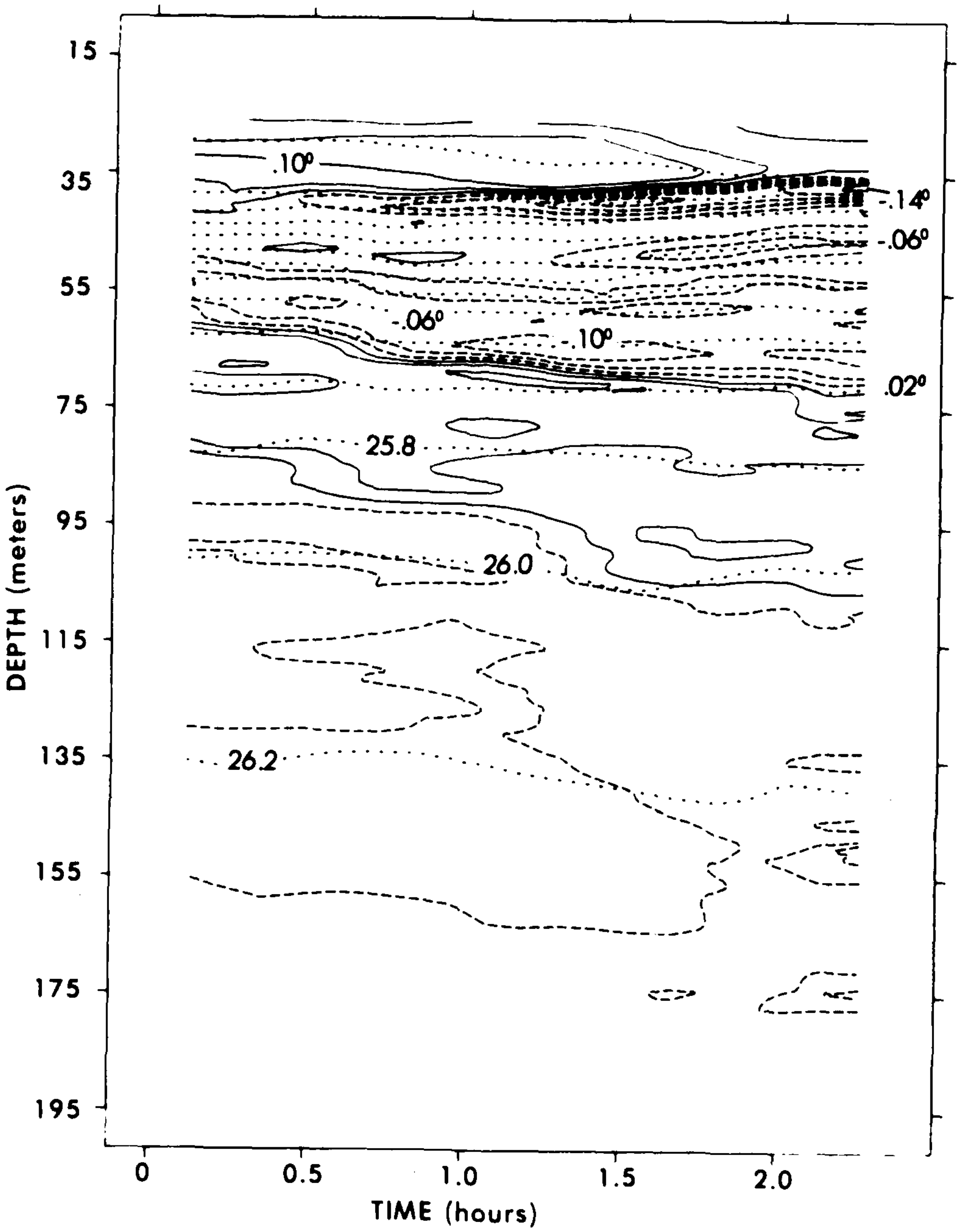

Figure 11. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26081. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

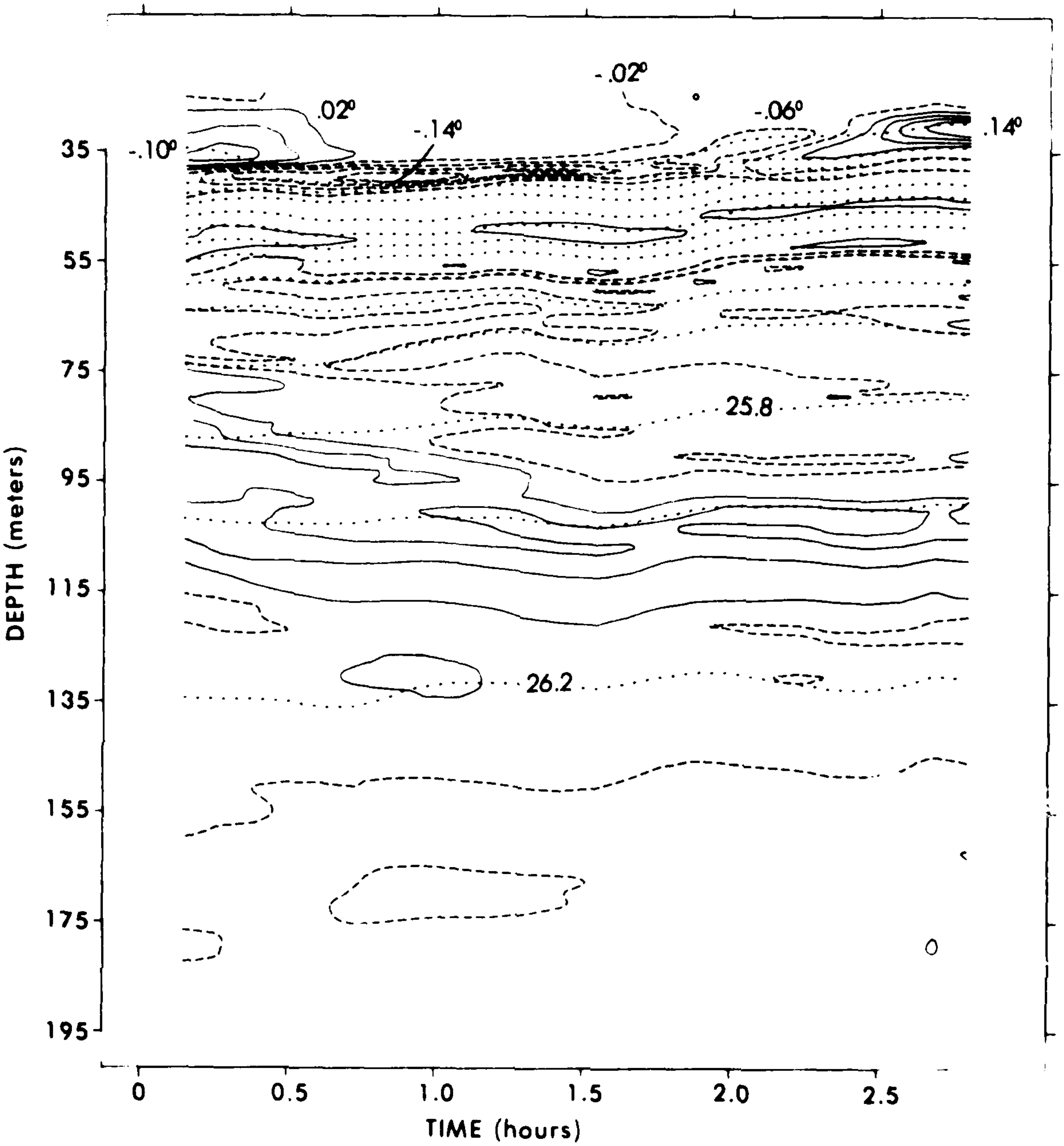

Figure 12. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26082. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

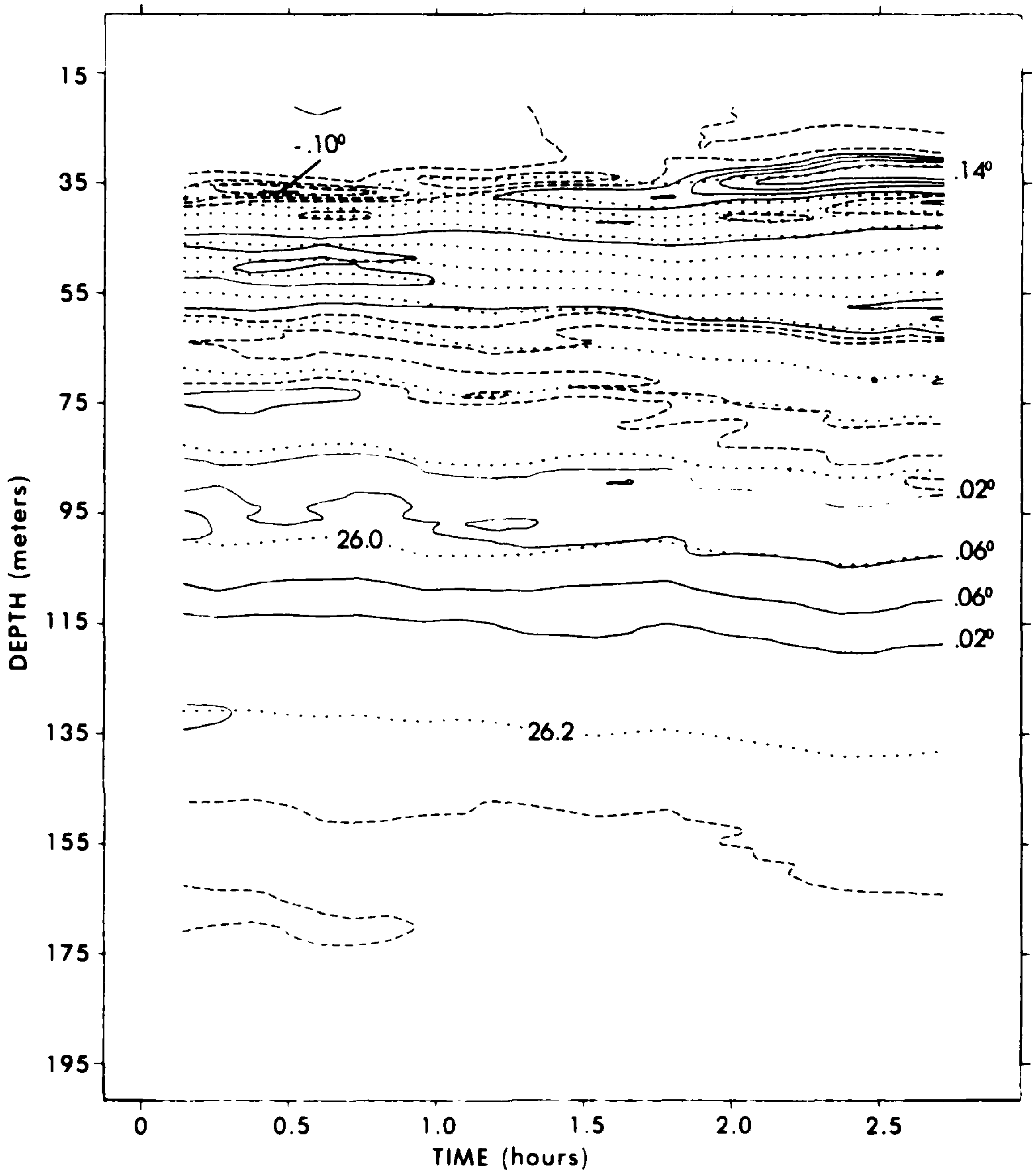

Figure 13. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26083. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

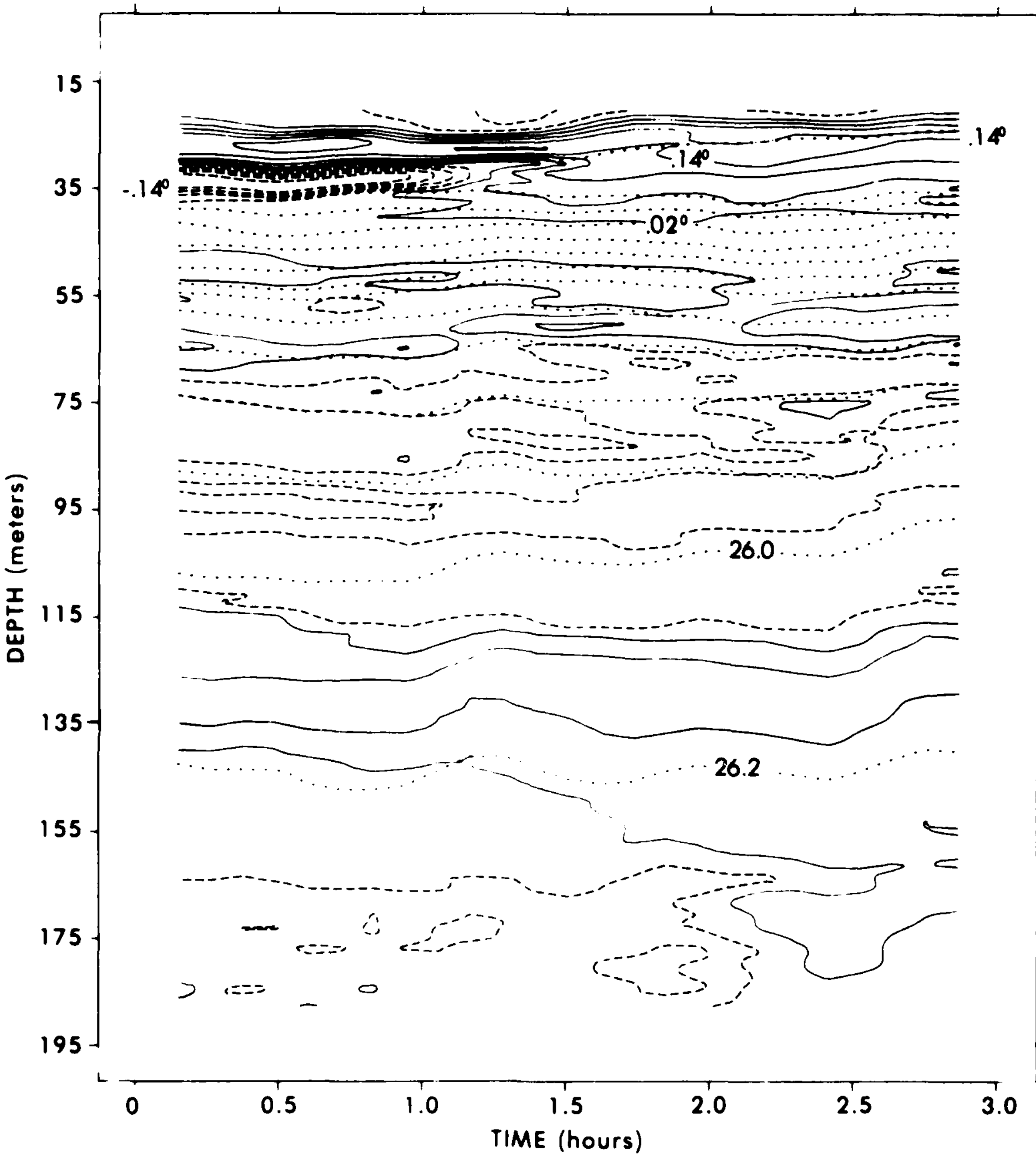

Figure 14. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26084. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

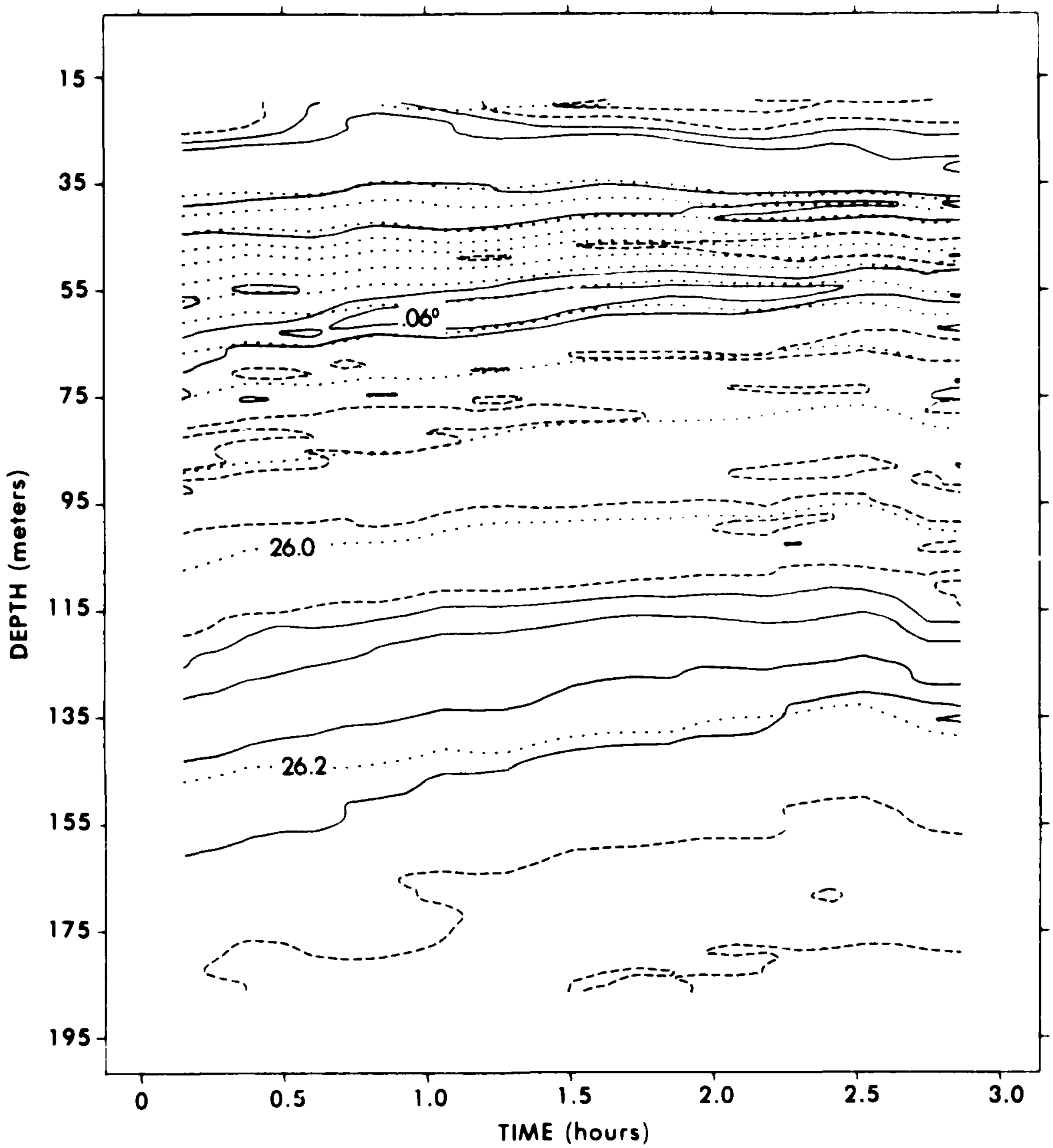

Figure 15. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26085. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

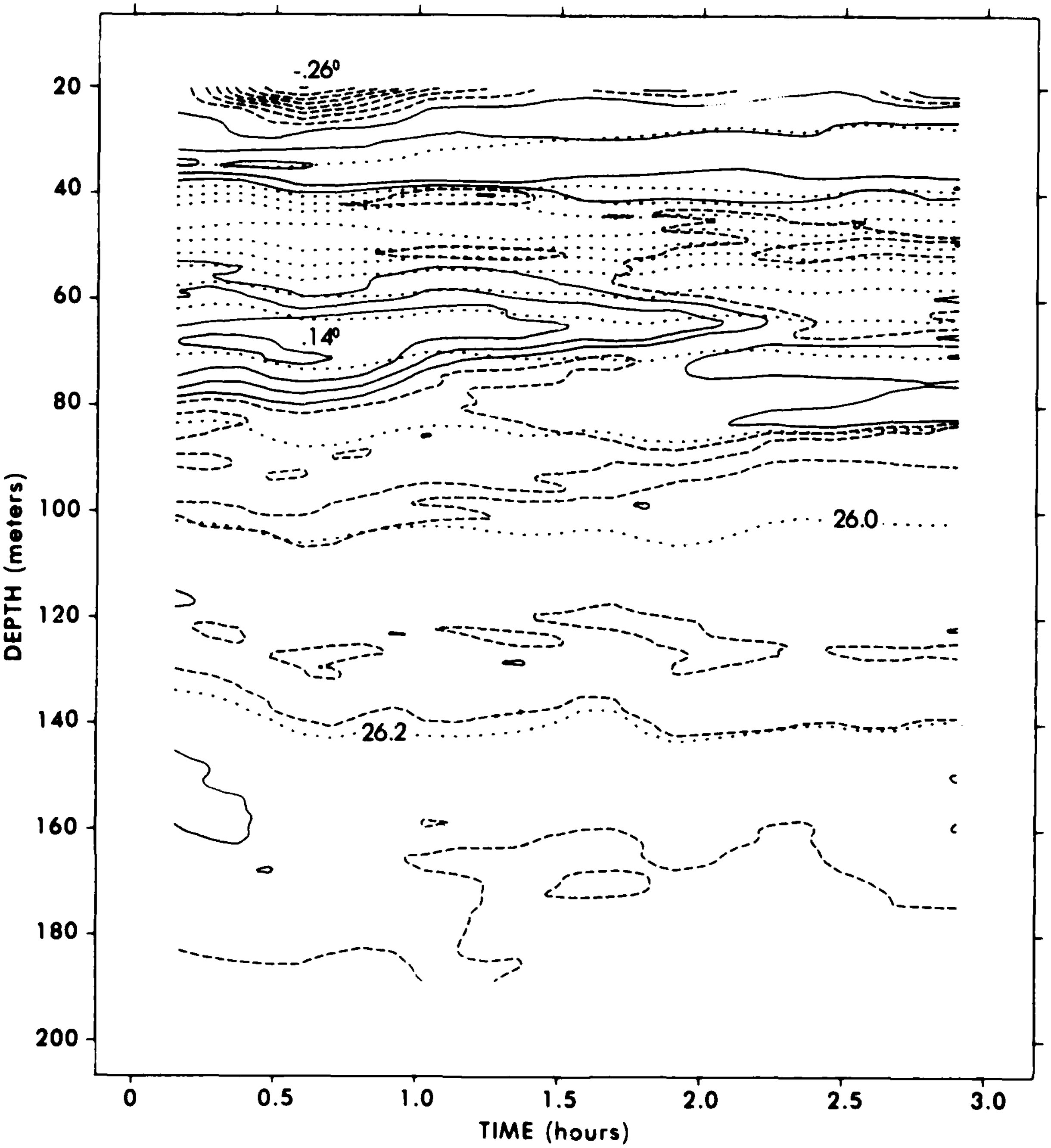

Figure 16. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26086. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

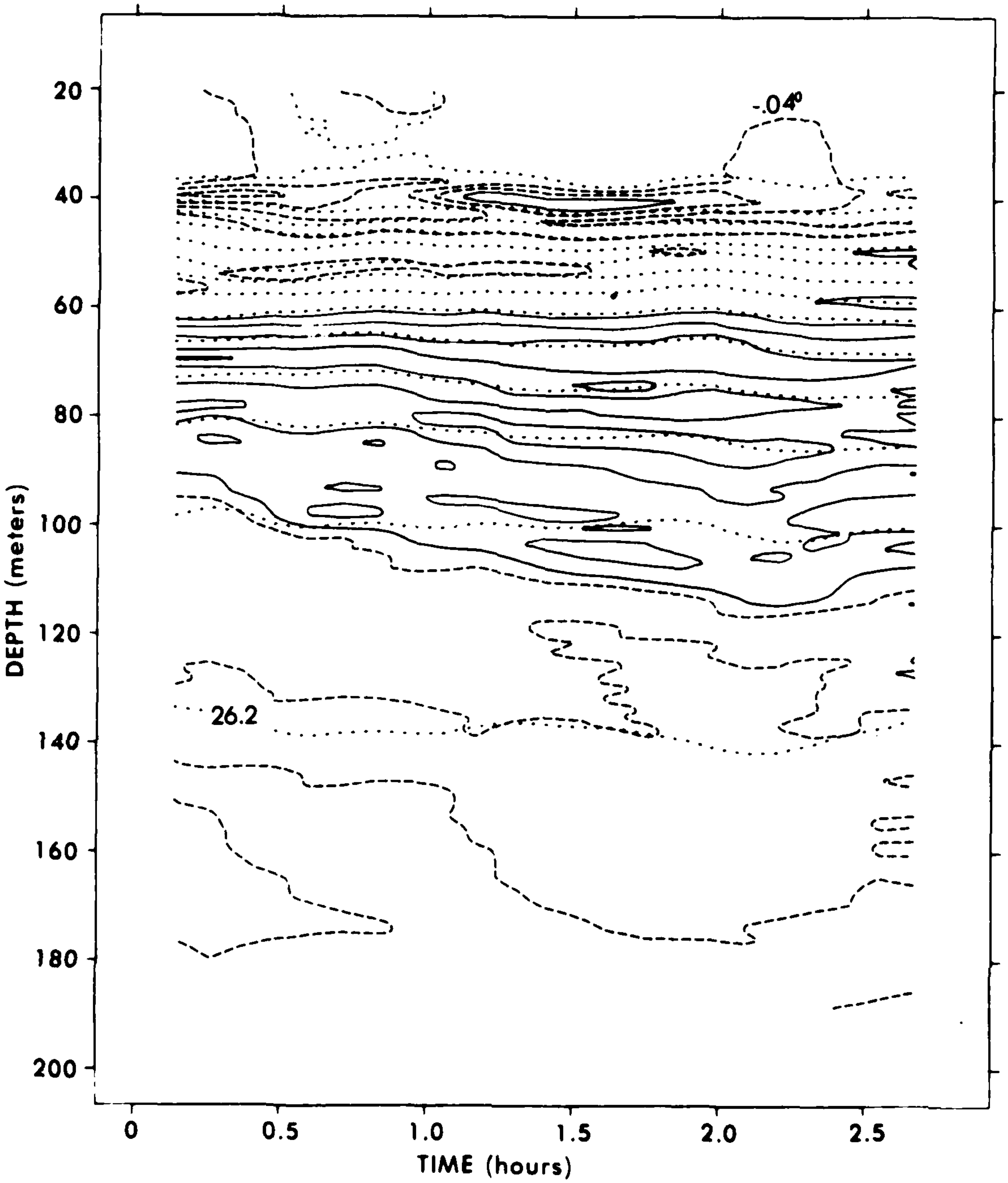

Figure 17. Isopycnal temperature anomalies and sigma-t for Sargasso Sea Station 26087. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.2; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1.5 km/hour.)

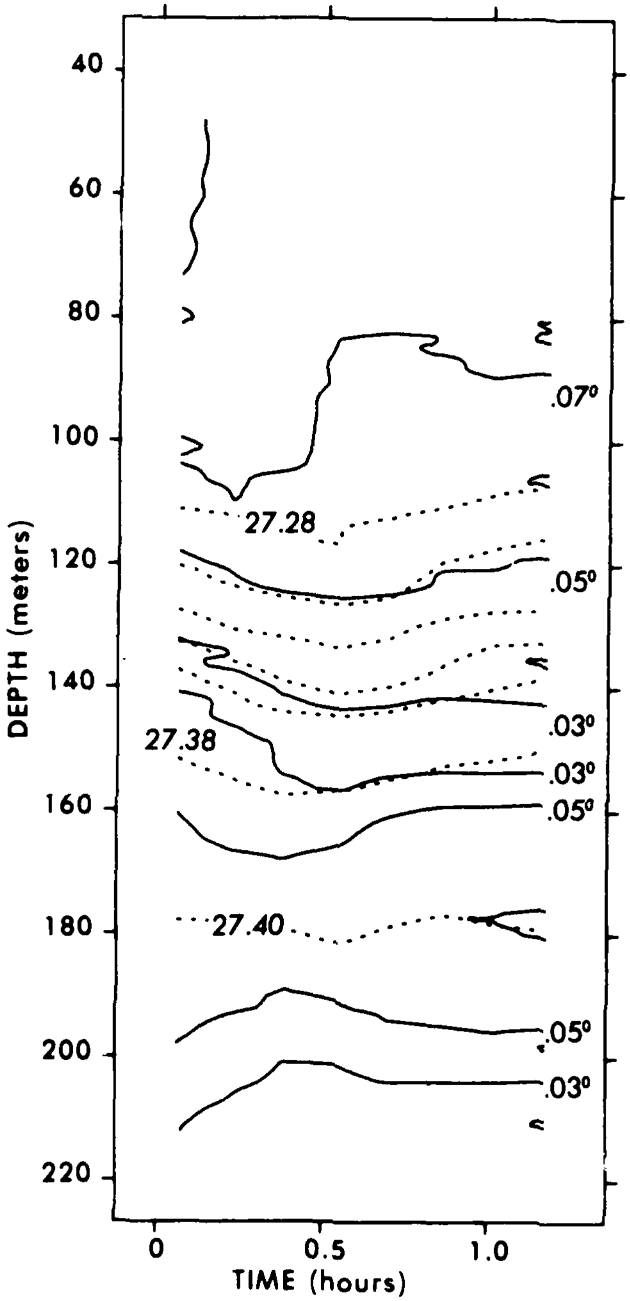

Figure 18. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109077. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

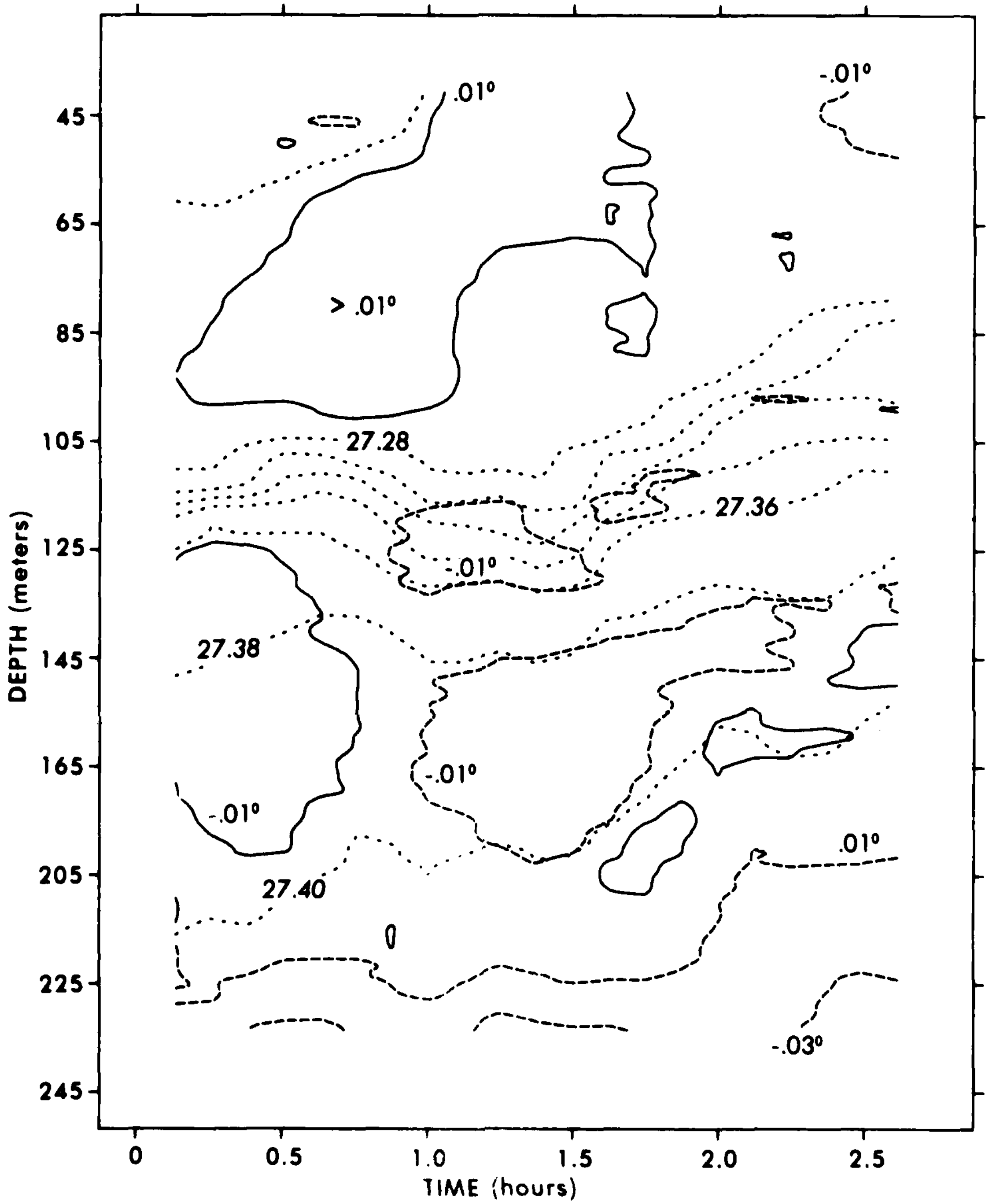

Figure 19. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109078. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

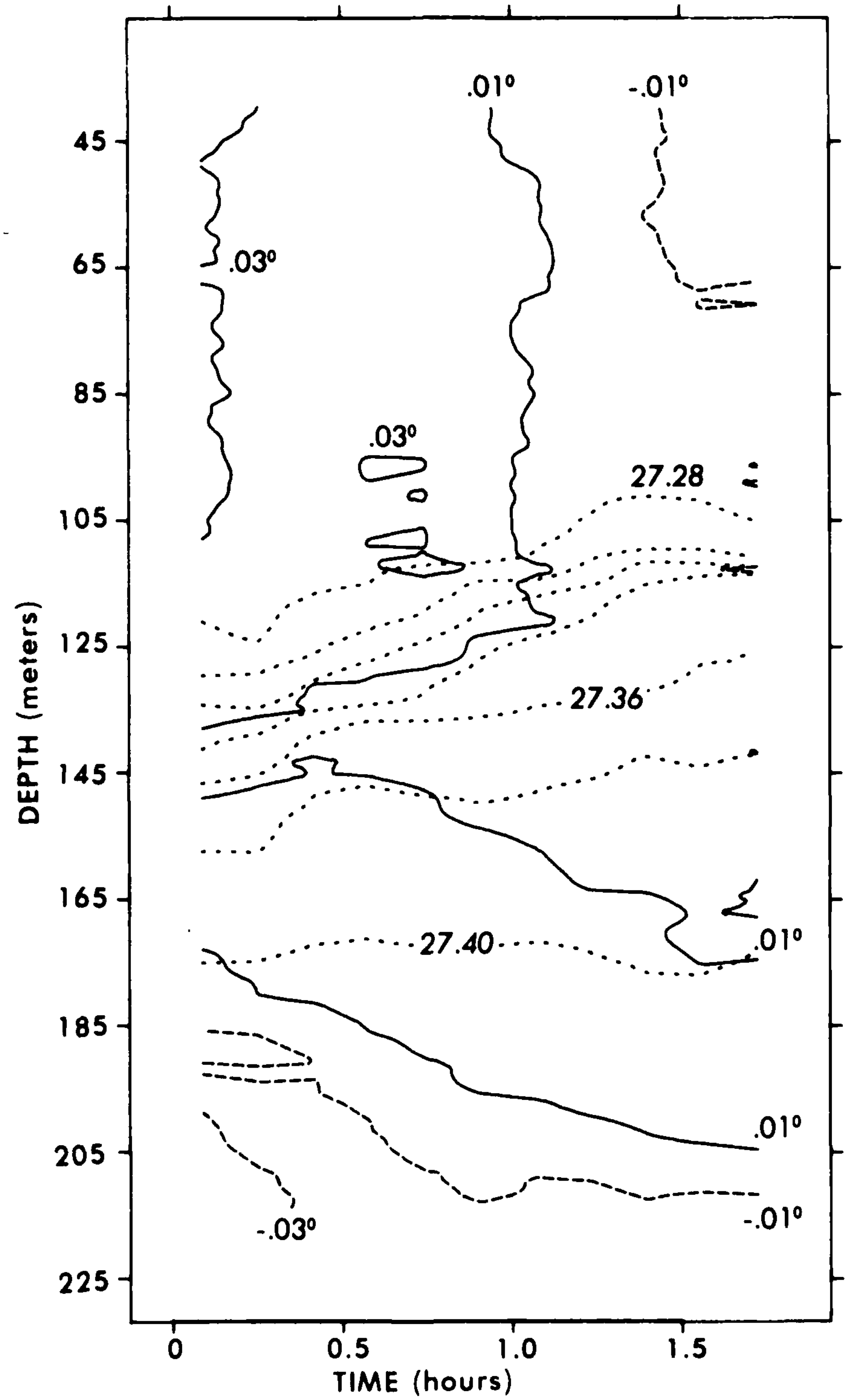

Figure 20. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109079. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

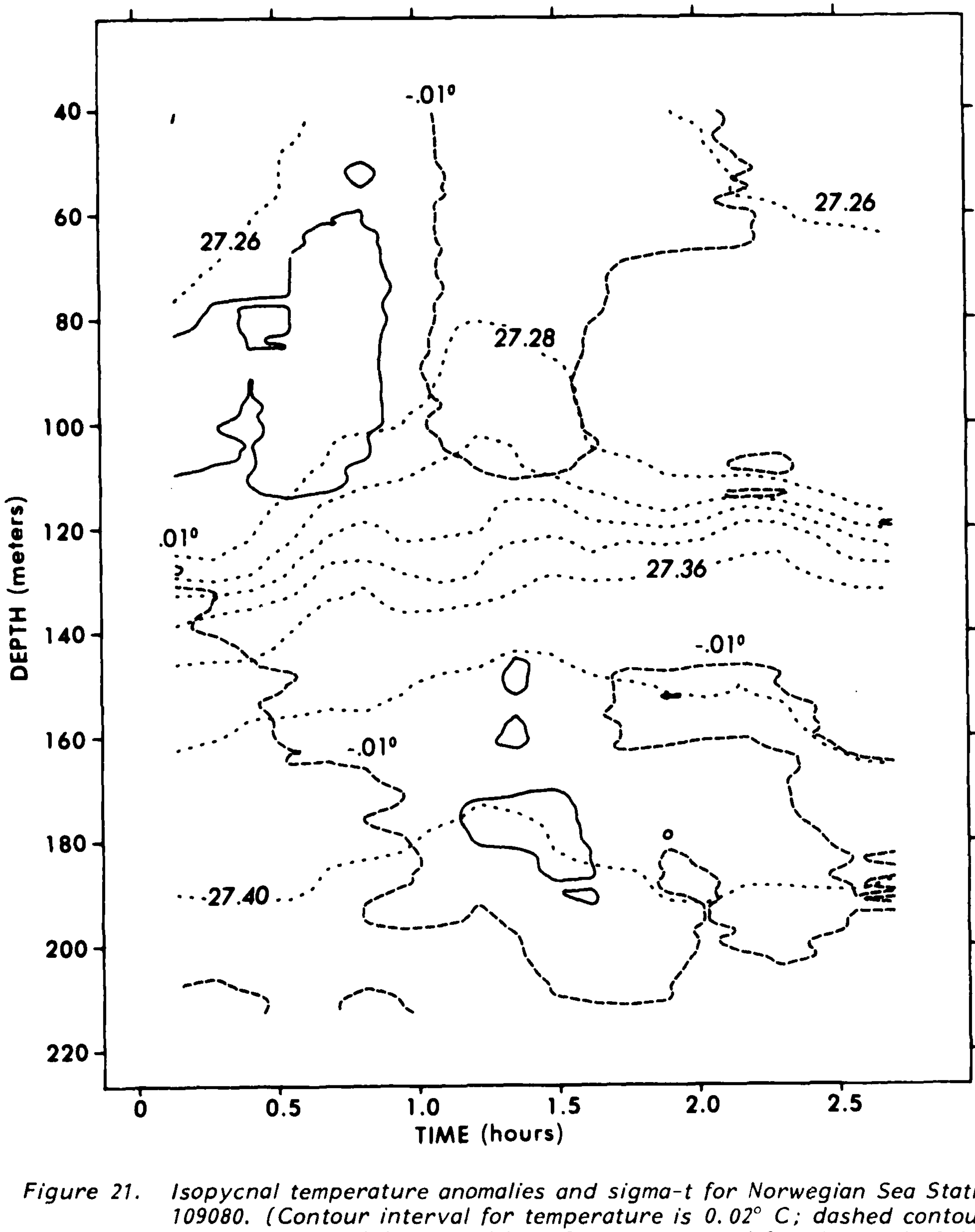

Figure 21. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109080. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

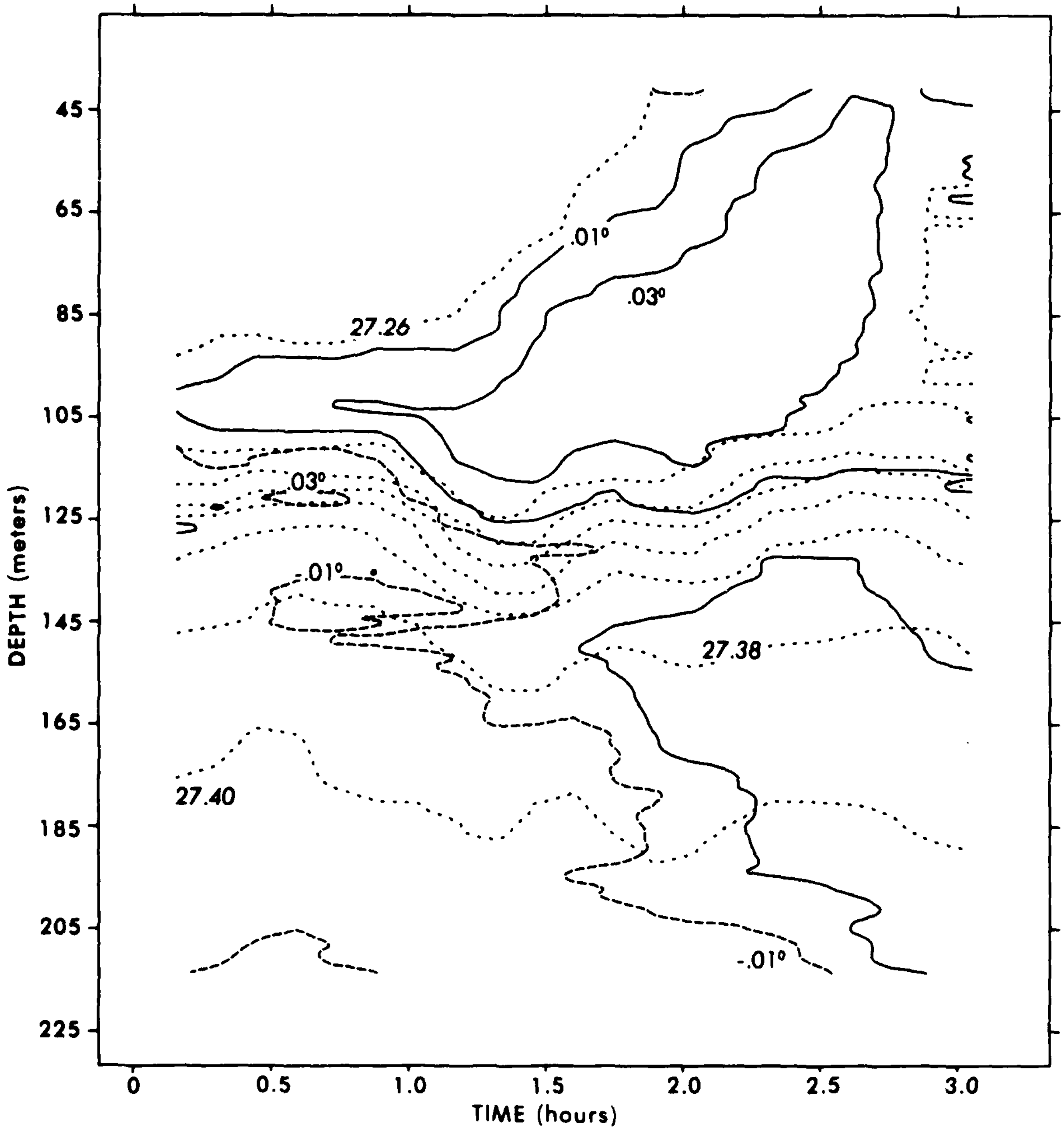

Figure 22. *Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109081. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)*

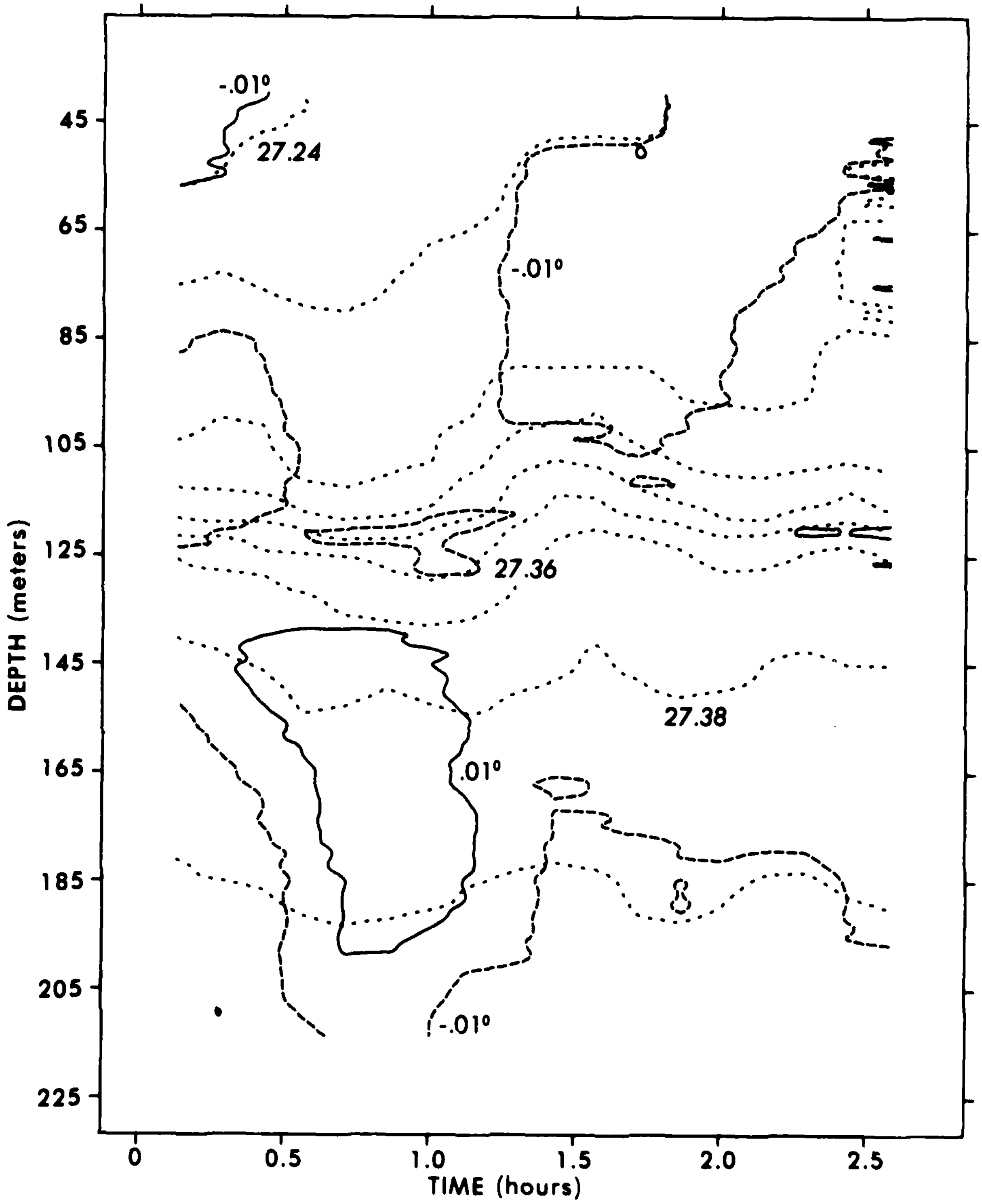

Figure 23. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109082. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

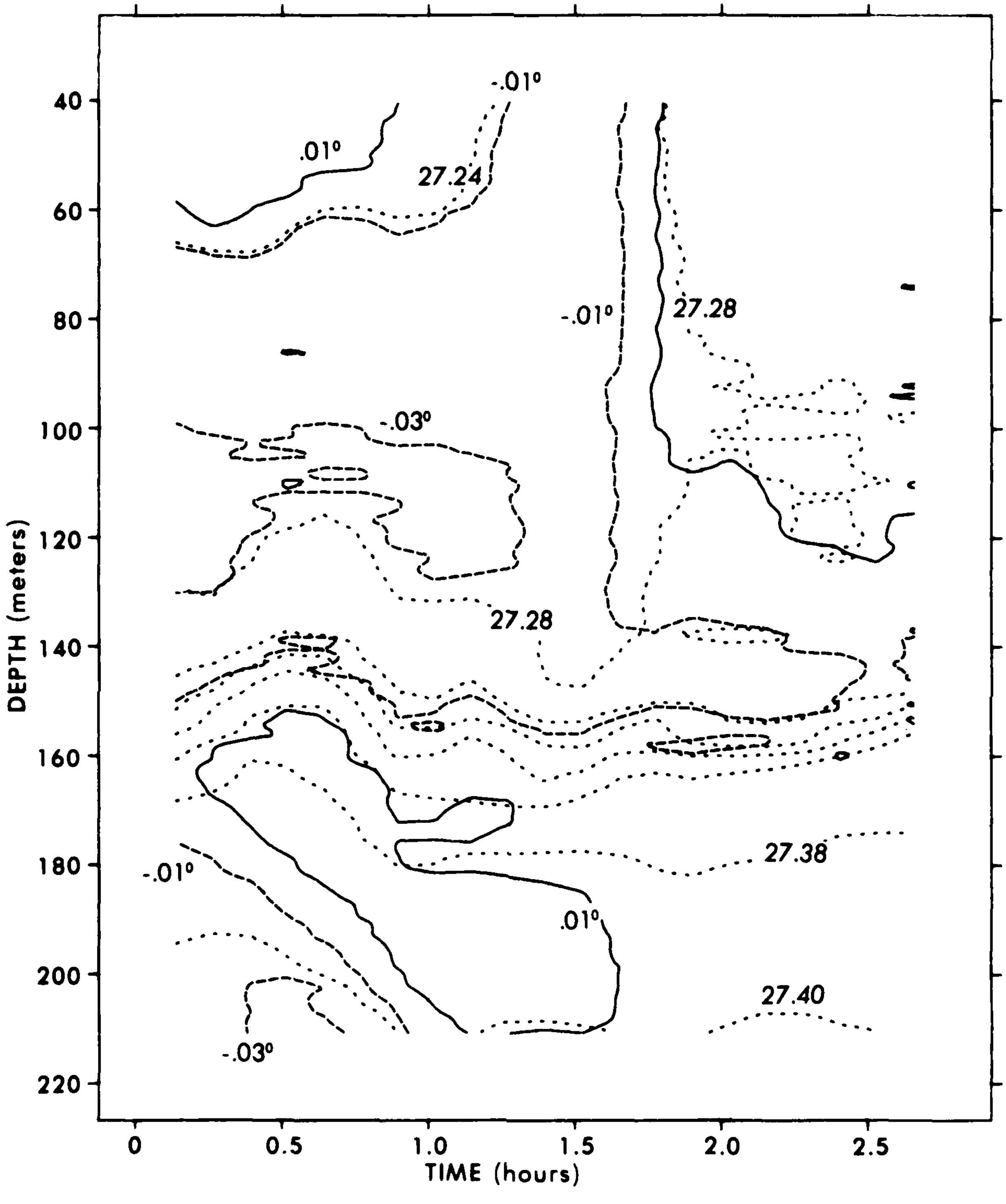

Figure 24. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 109083. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.02; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

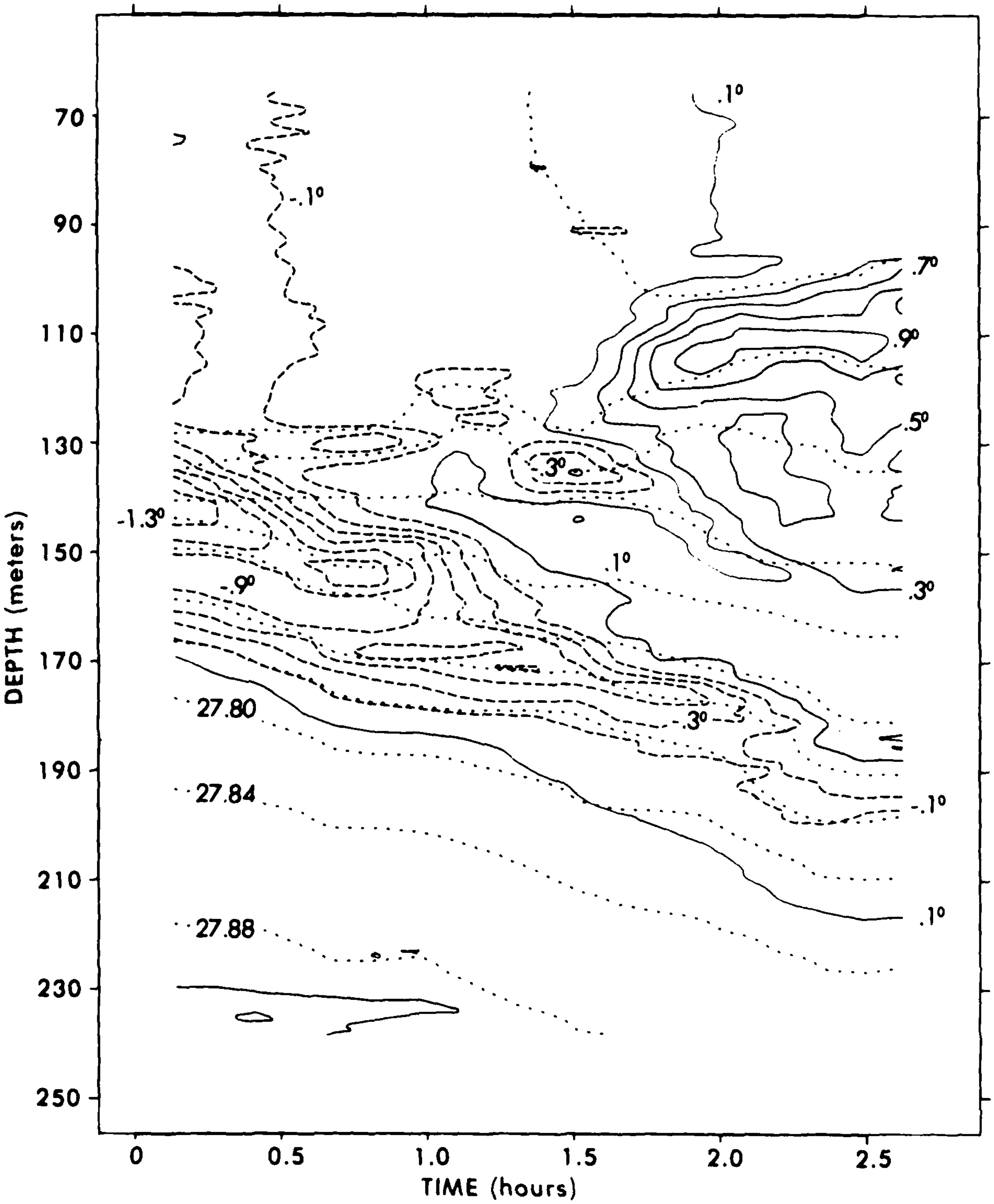

Figure 25. Isopycnal tempe, ature anomalies and sigma-t for Norwegian Sea Station 117092. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/nour.)

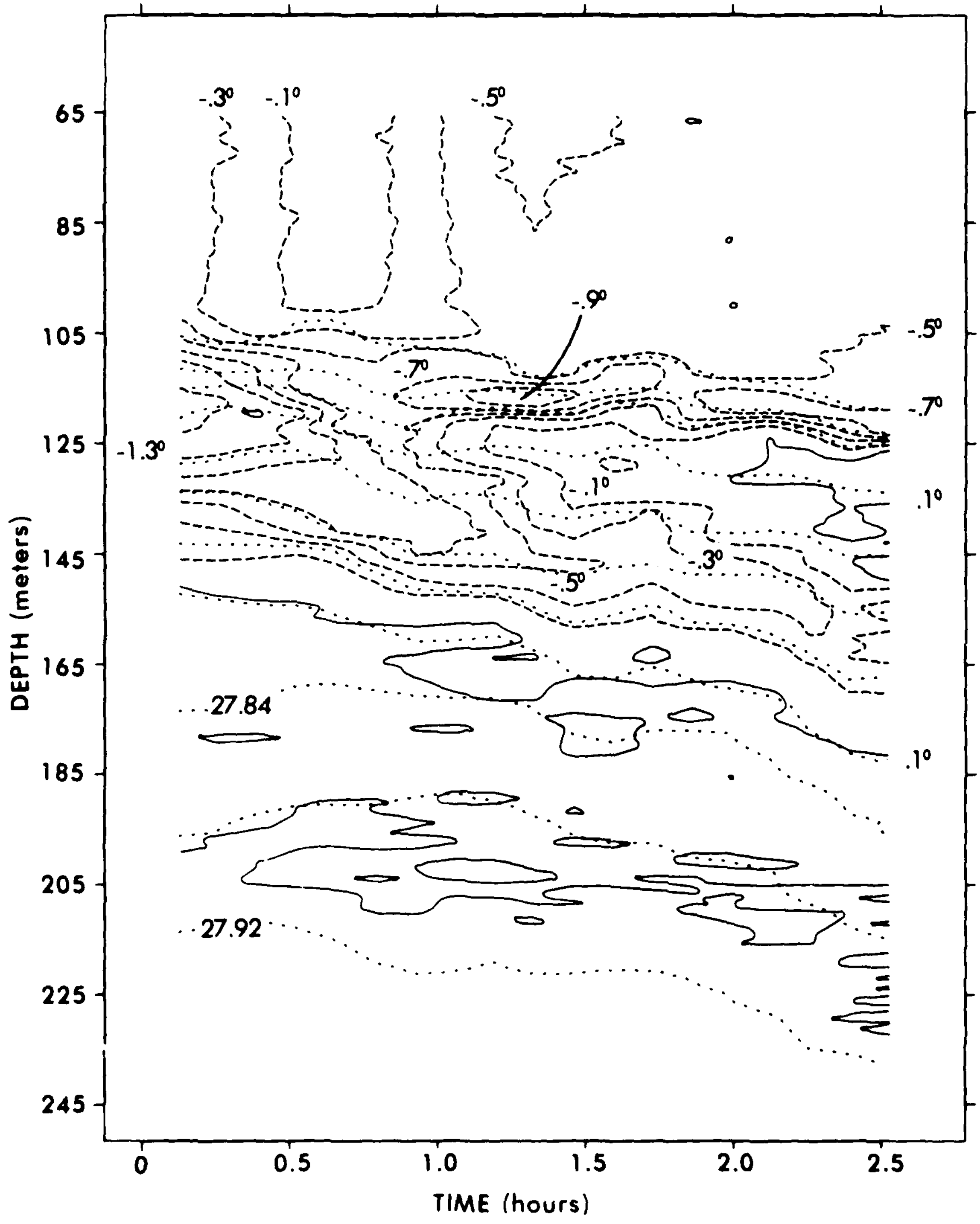

Figure 26. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117093. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

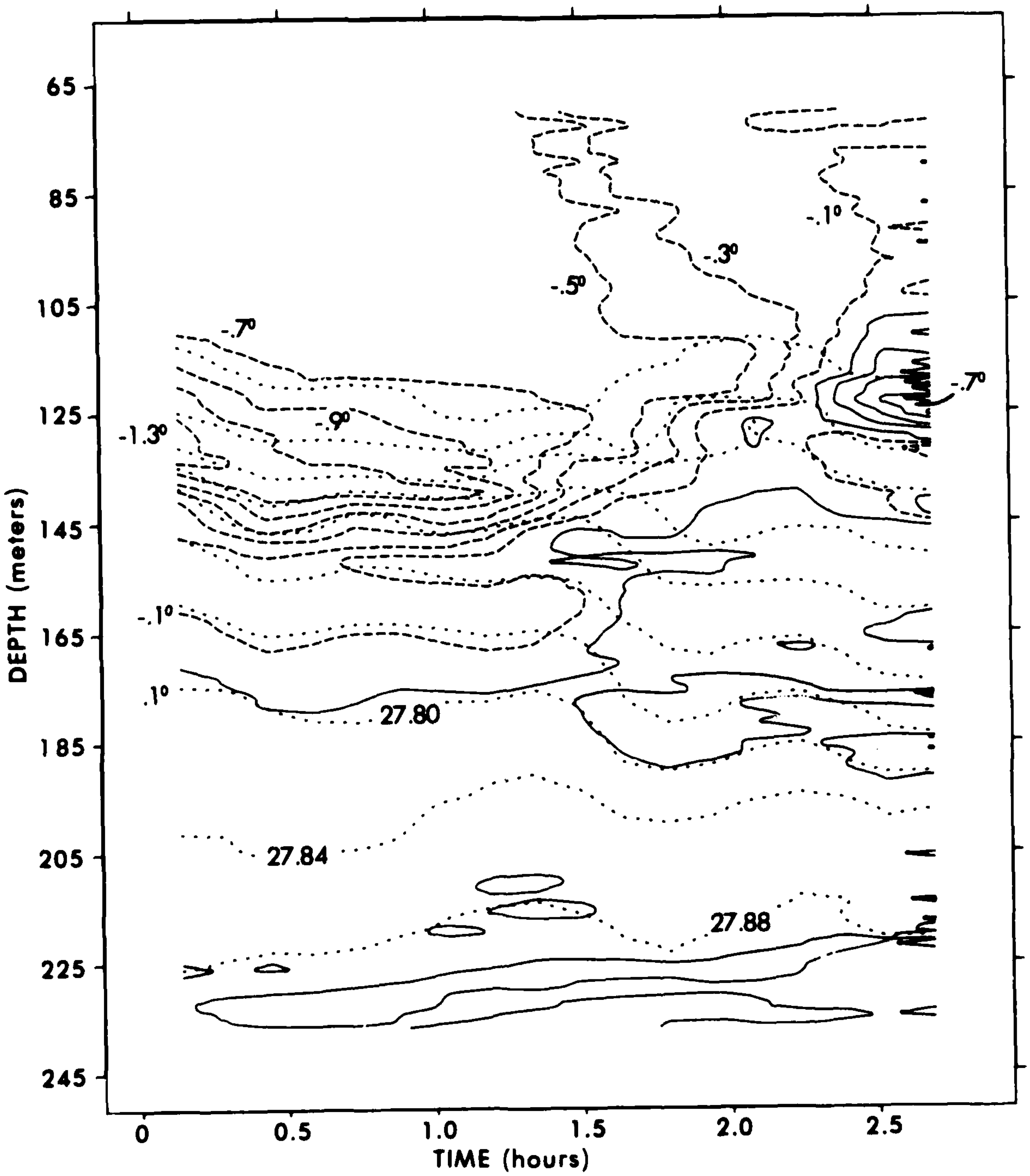

Figure 27. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117094. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

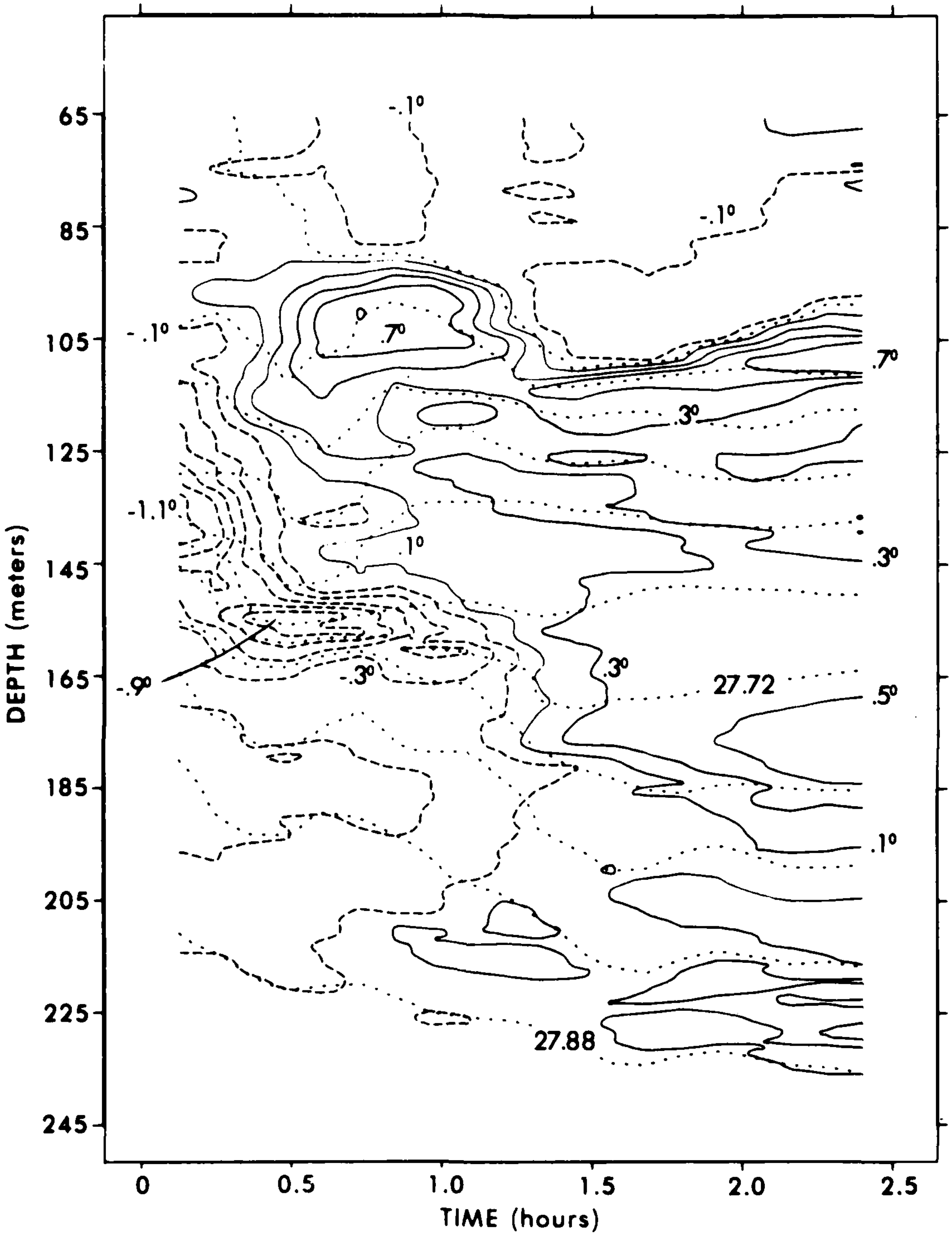

Figure 28. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117095. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

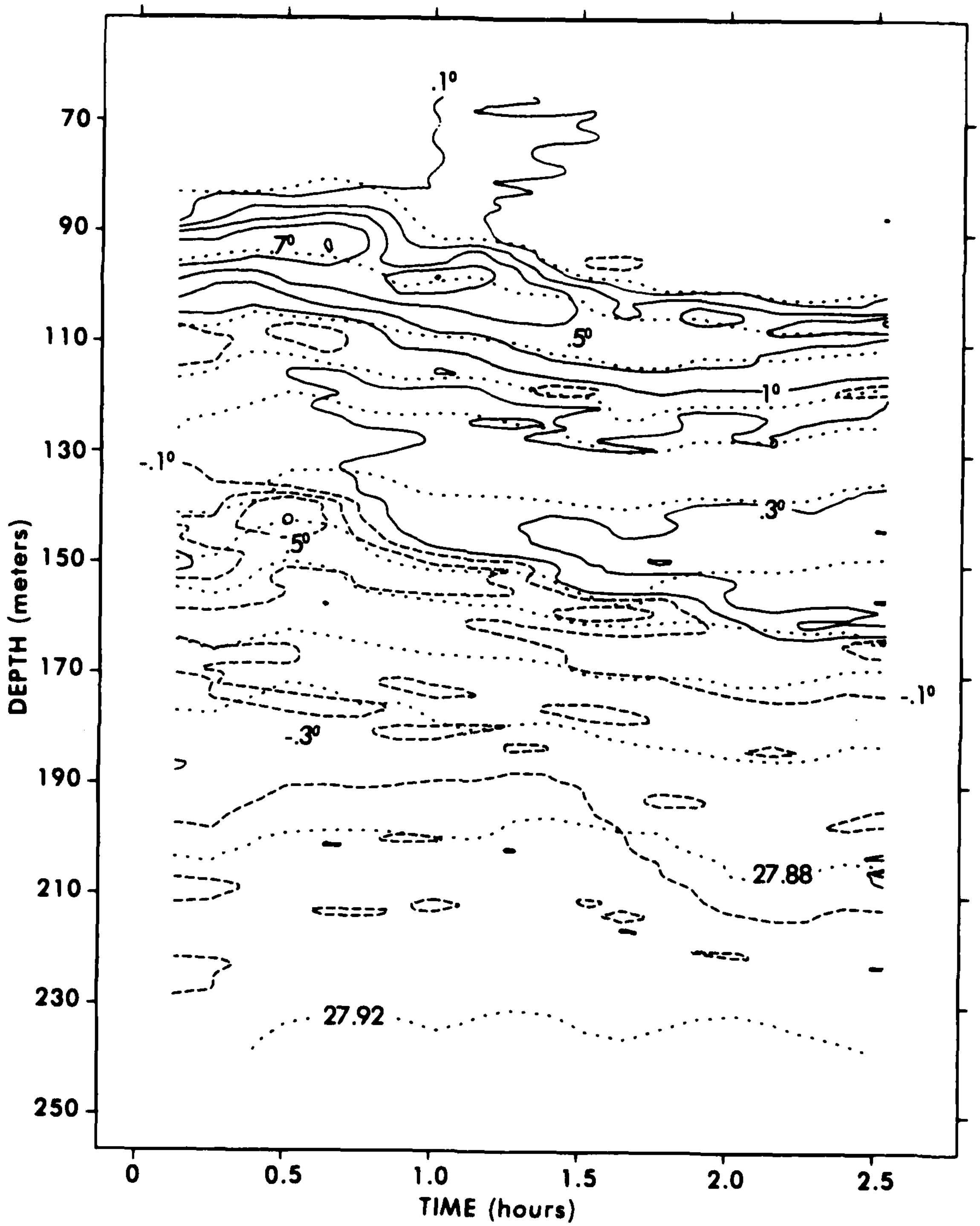

Figure 29. *Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117096. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)*

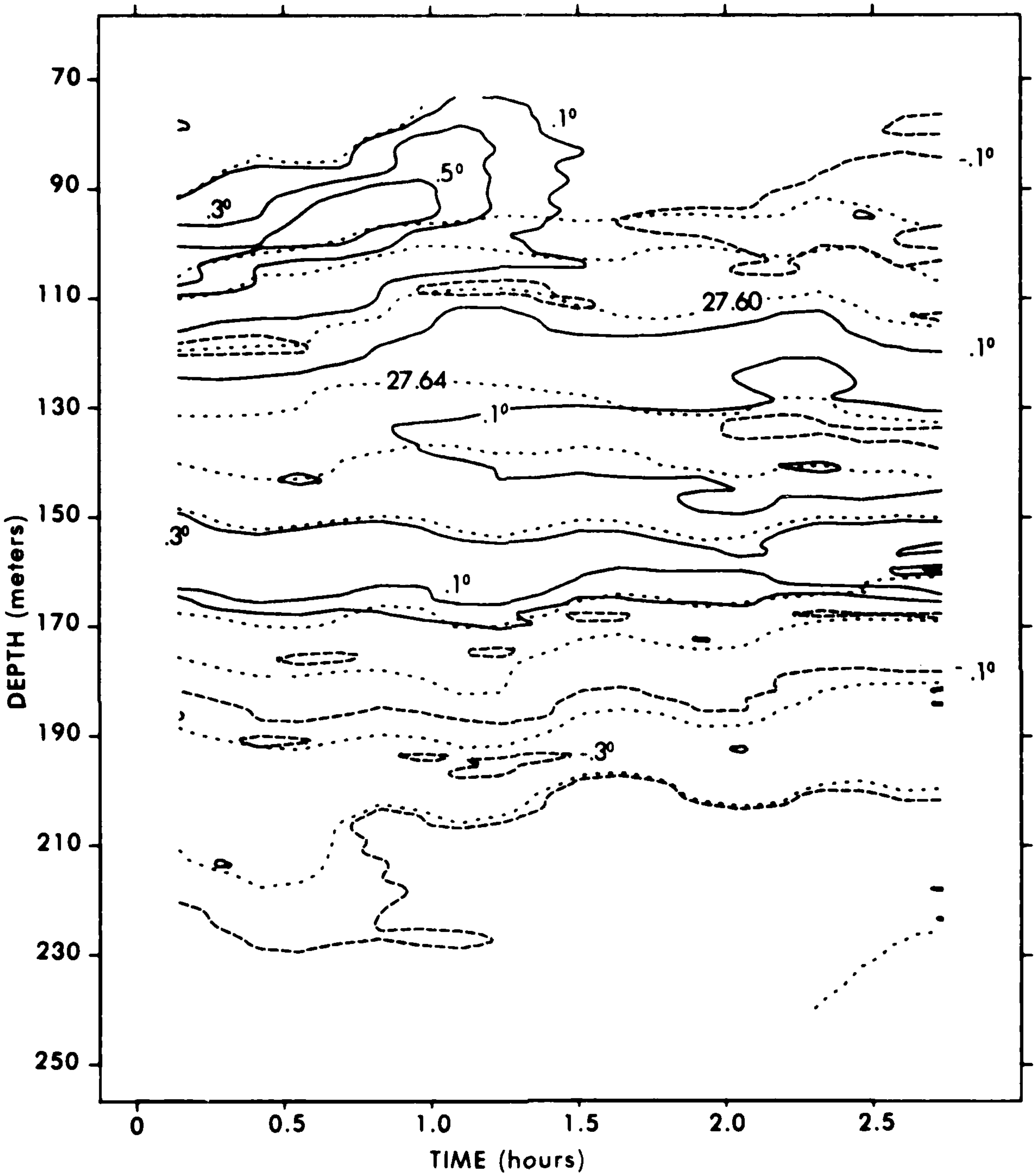

Figure 30. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117097. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

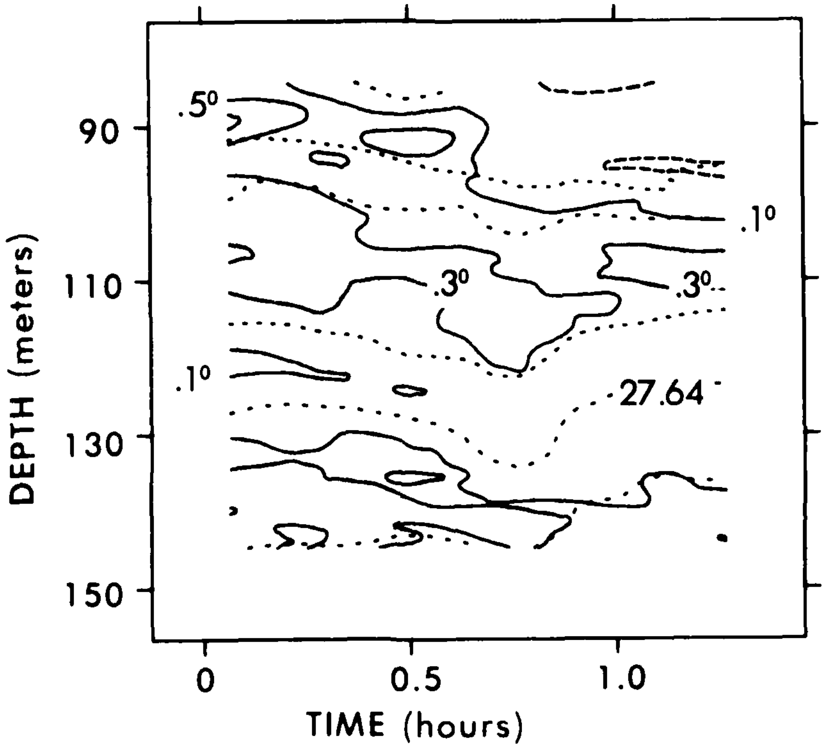

Figure 31. *Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 117098. (Contour interval is 0.2° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)*

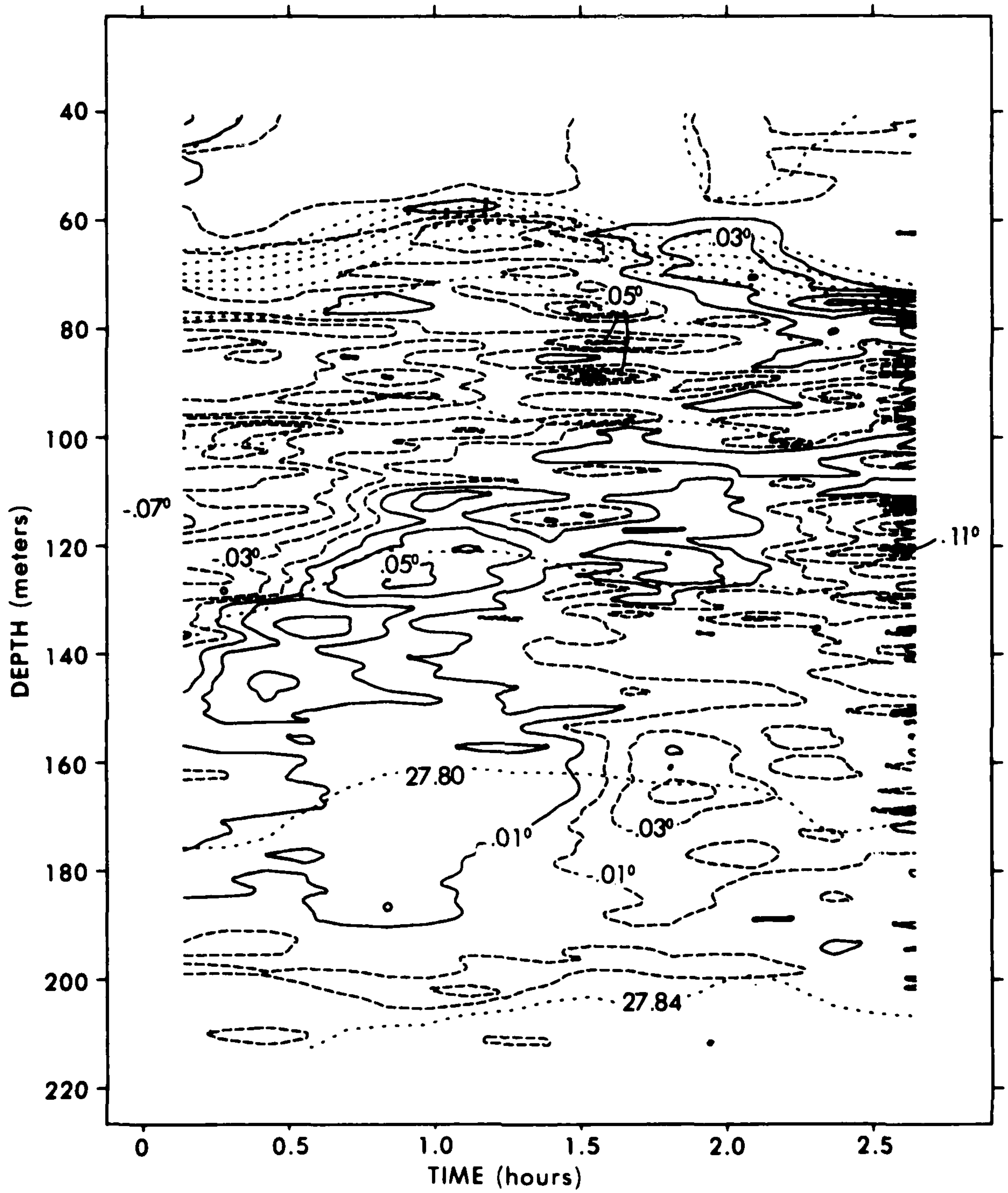

Figure 32. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 171148. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

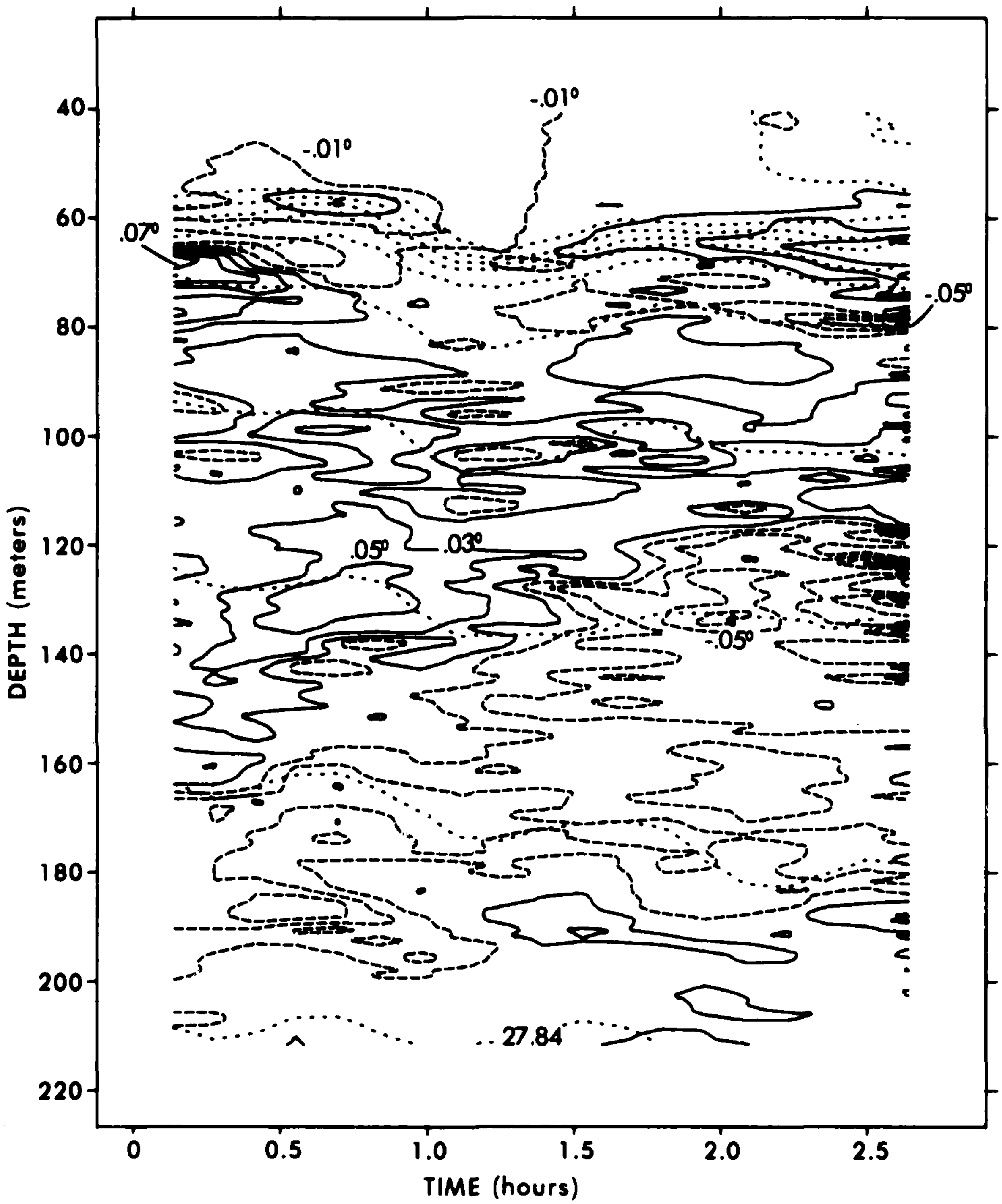

Figure 33. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 171149. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

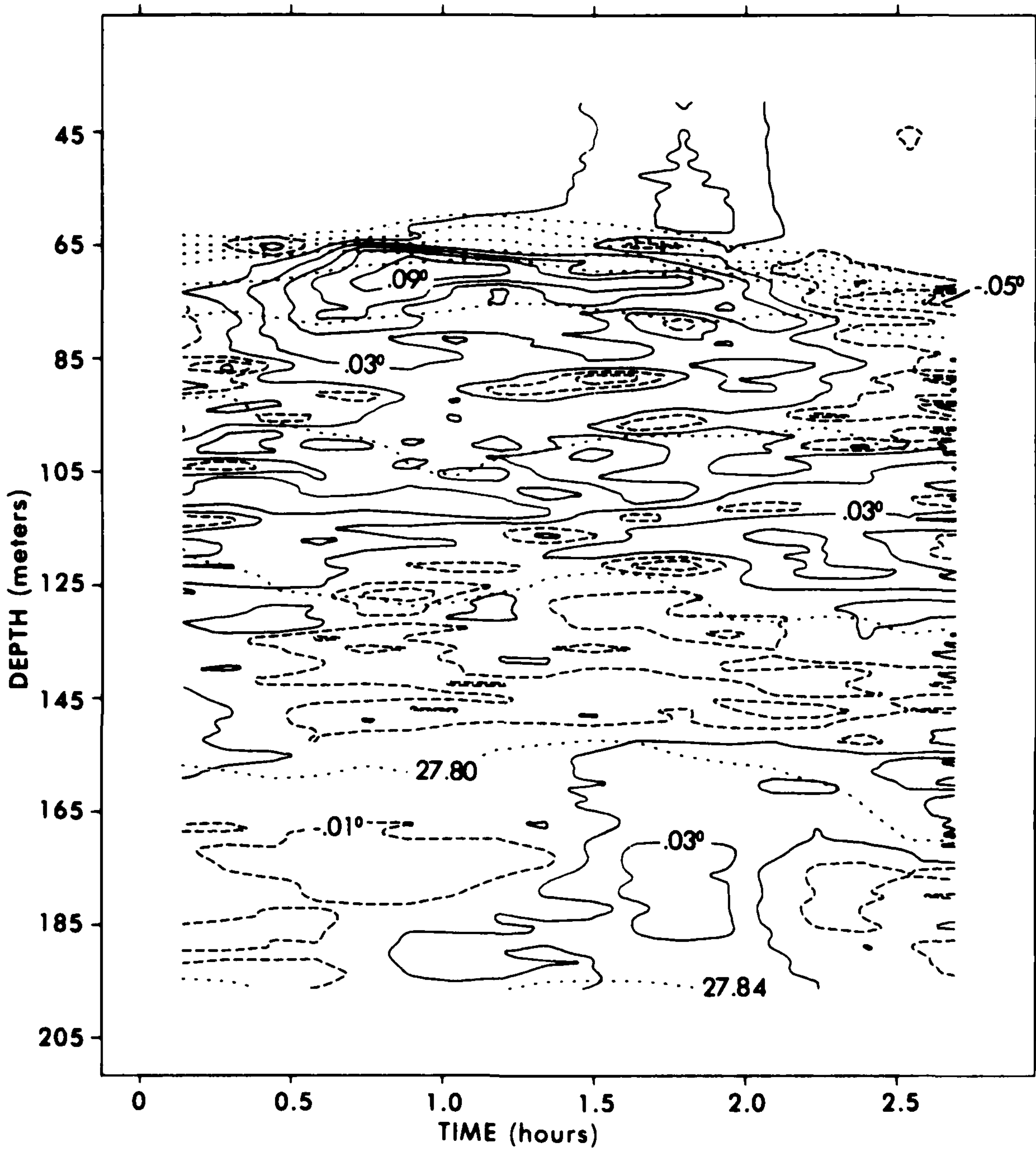

Figure 34. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 171150. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

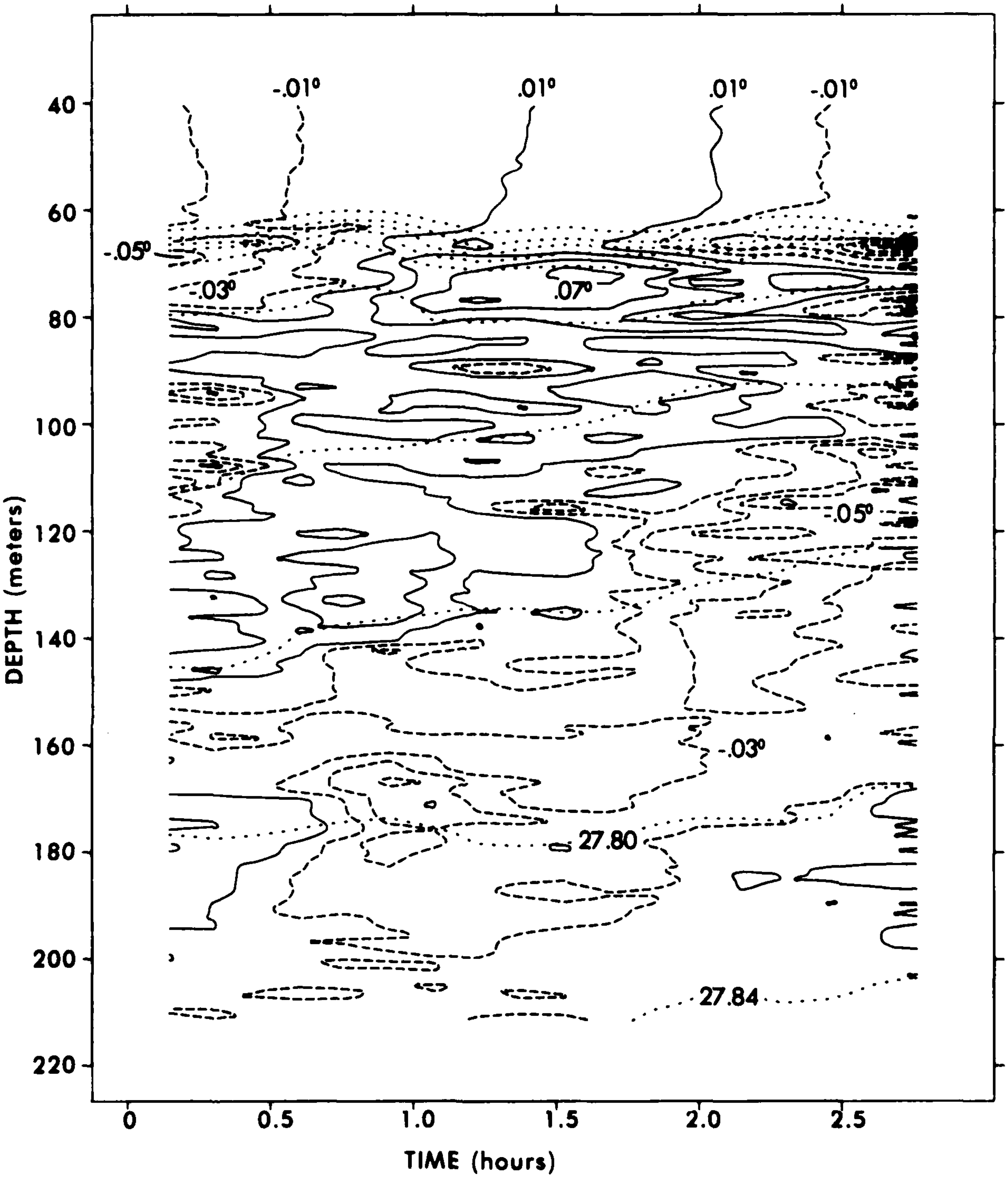

Figure 35. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 171151. (Contour interval for temperature is 0.02° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

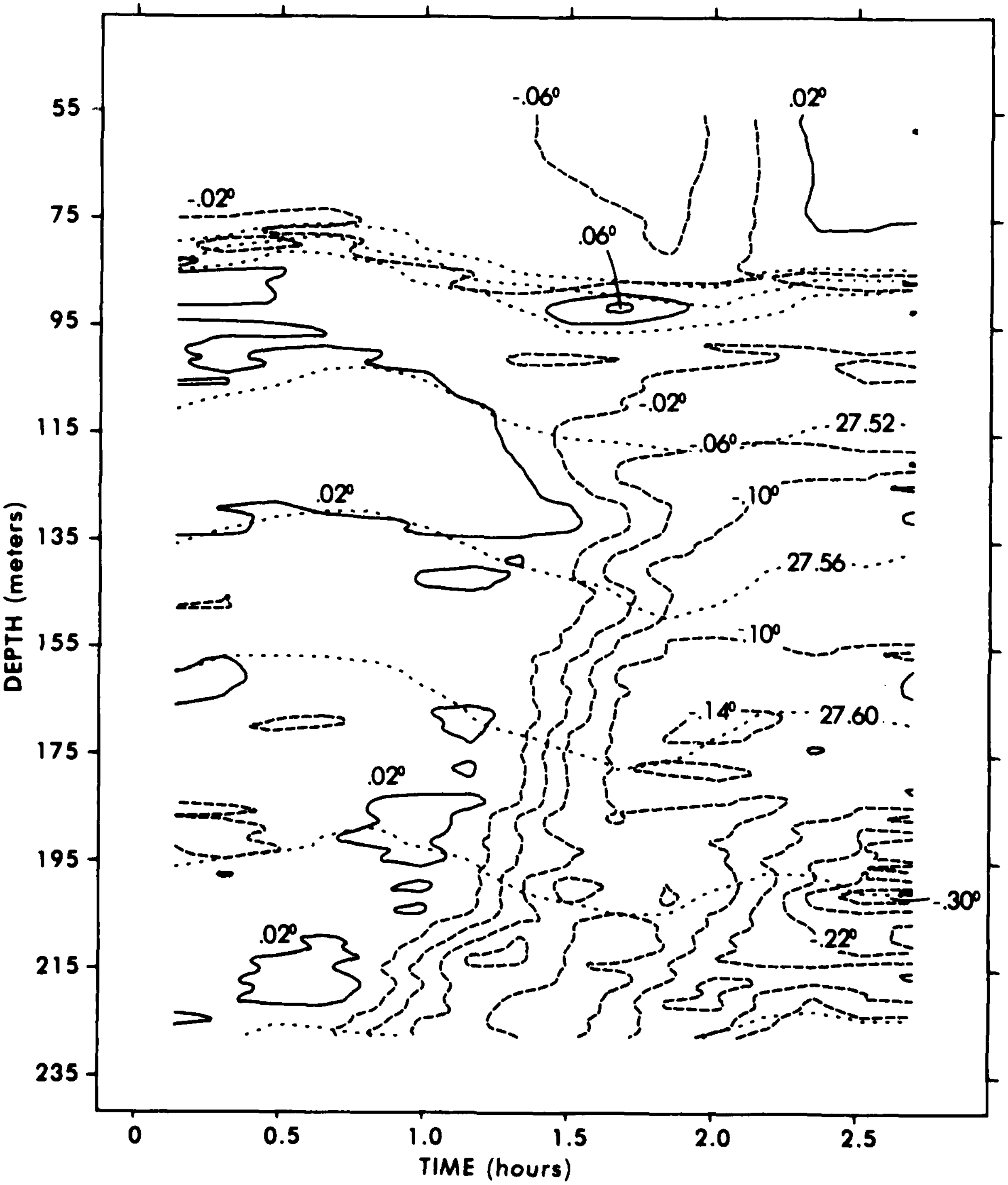

Figure 36. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175156. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

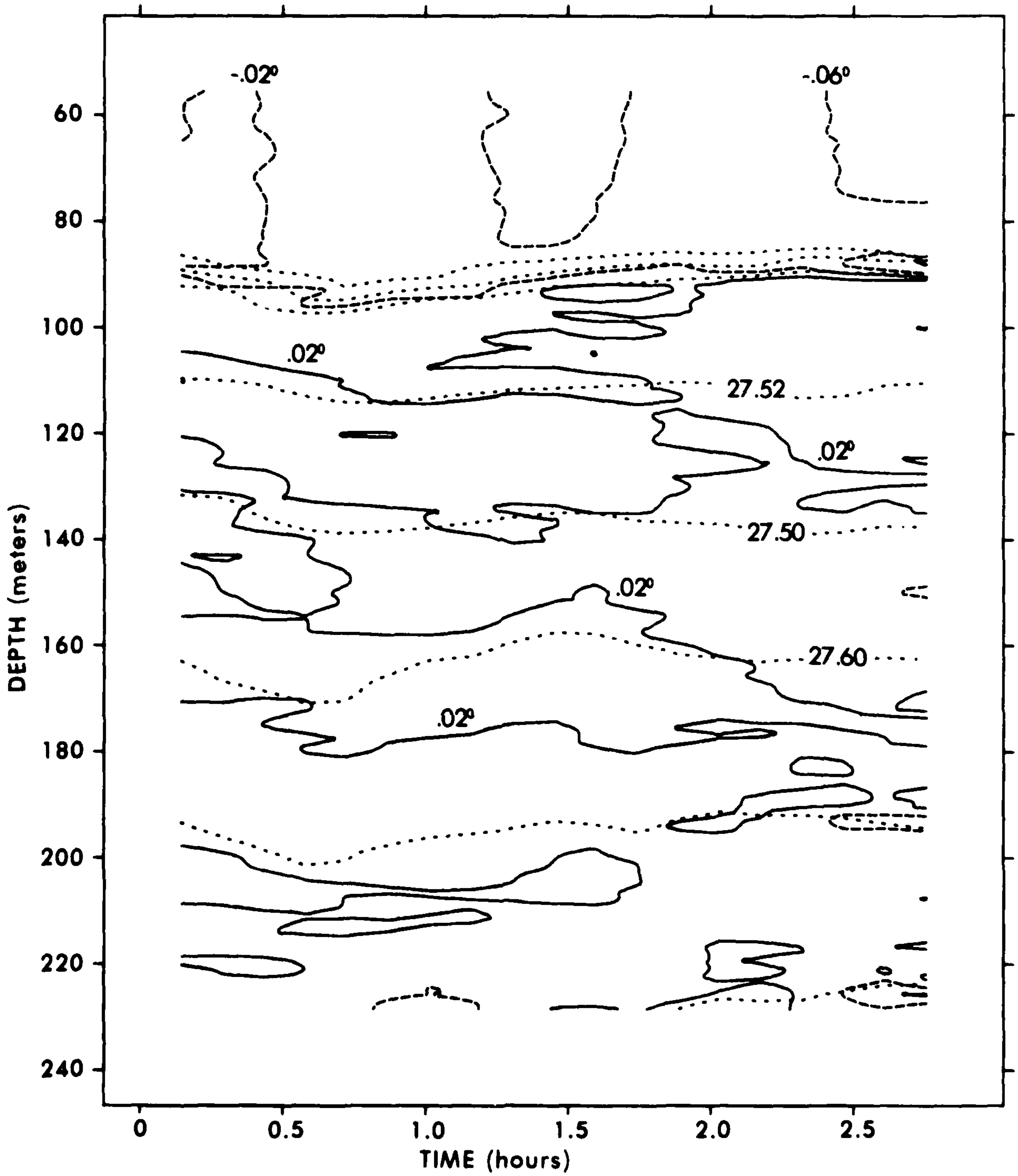

Figure 37. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175157. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

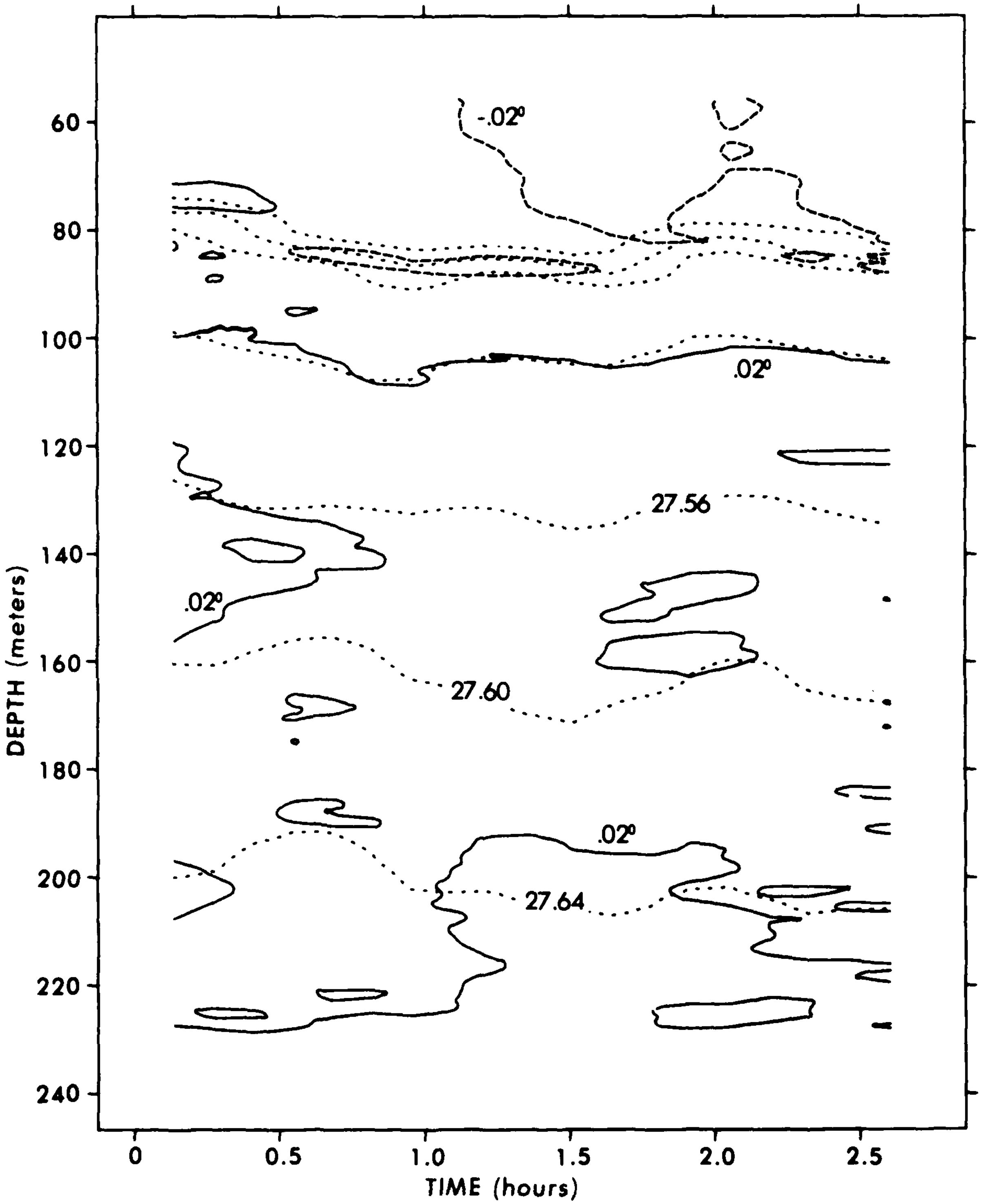

Figure 38. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175158. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

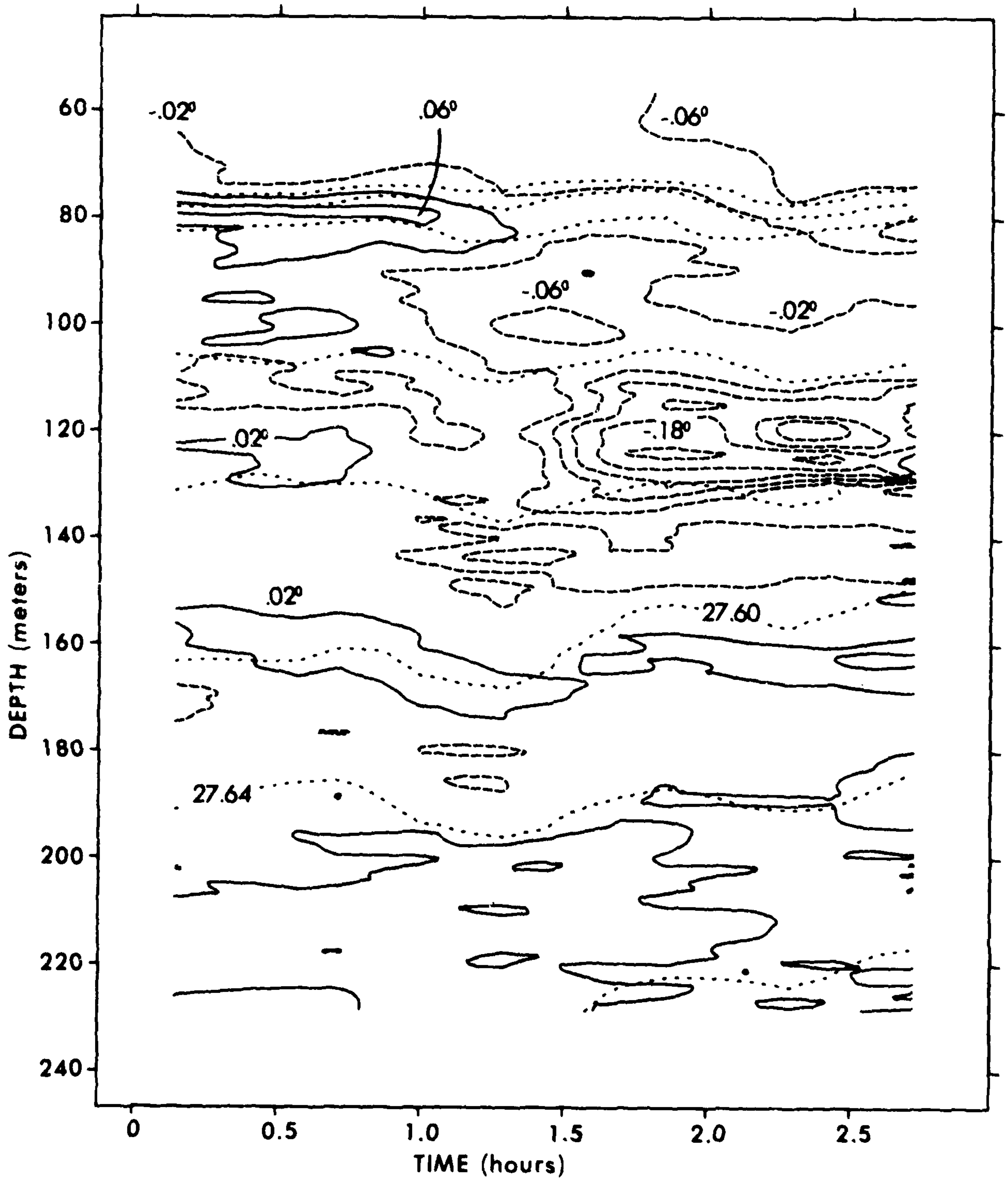

Figure 39. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175159. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

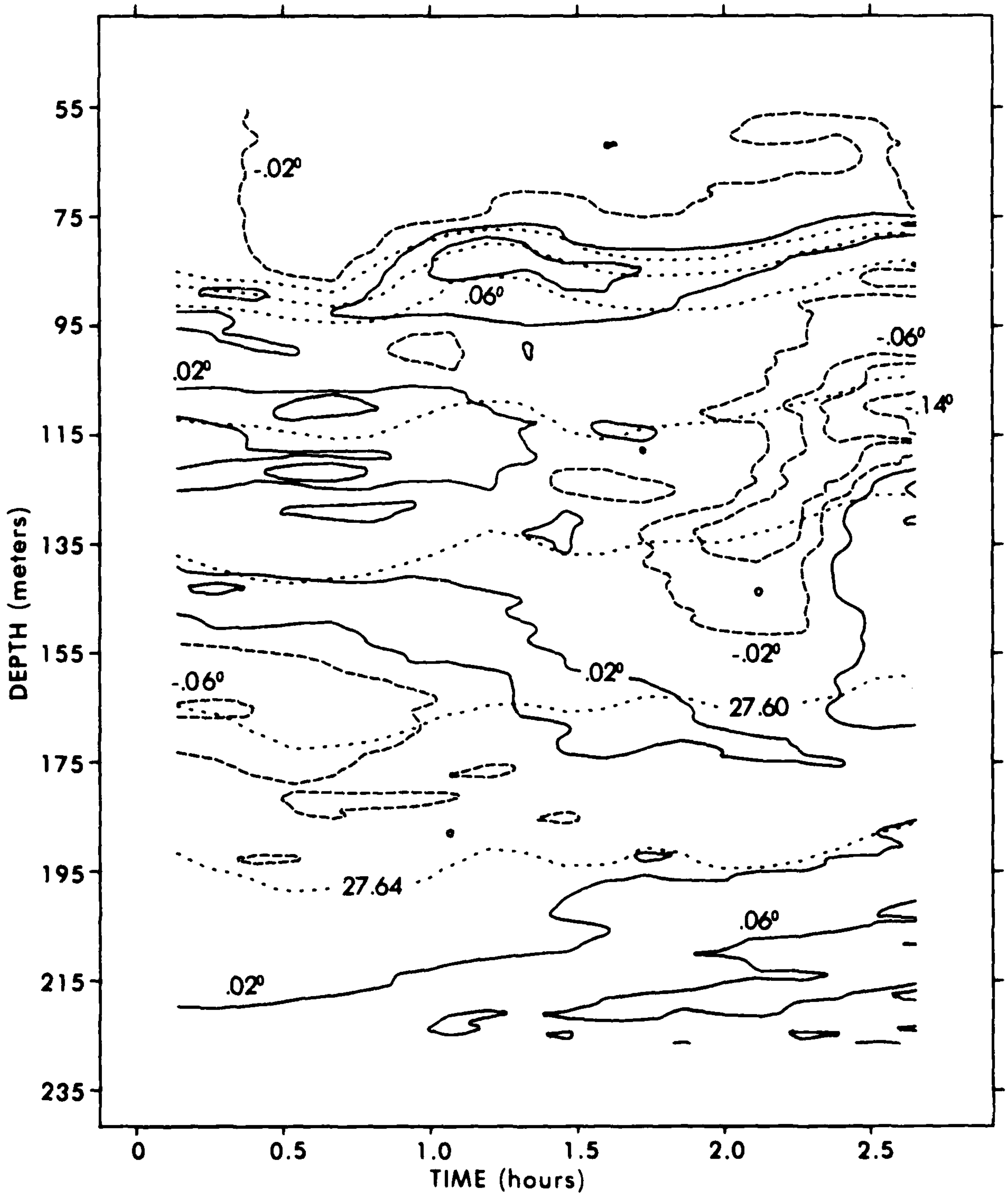

Figure 40. *Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175160. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.4; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)*

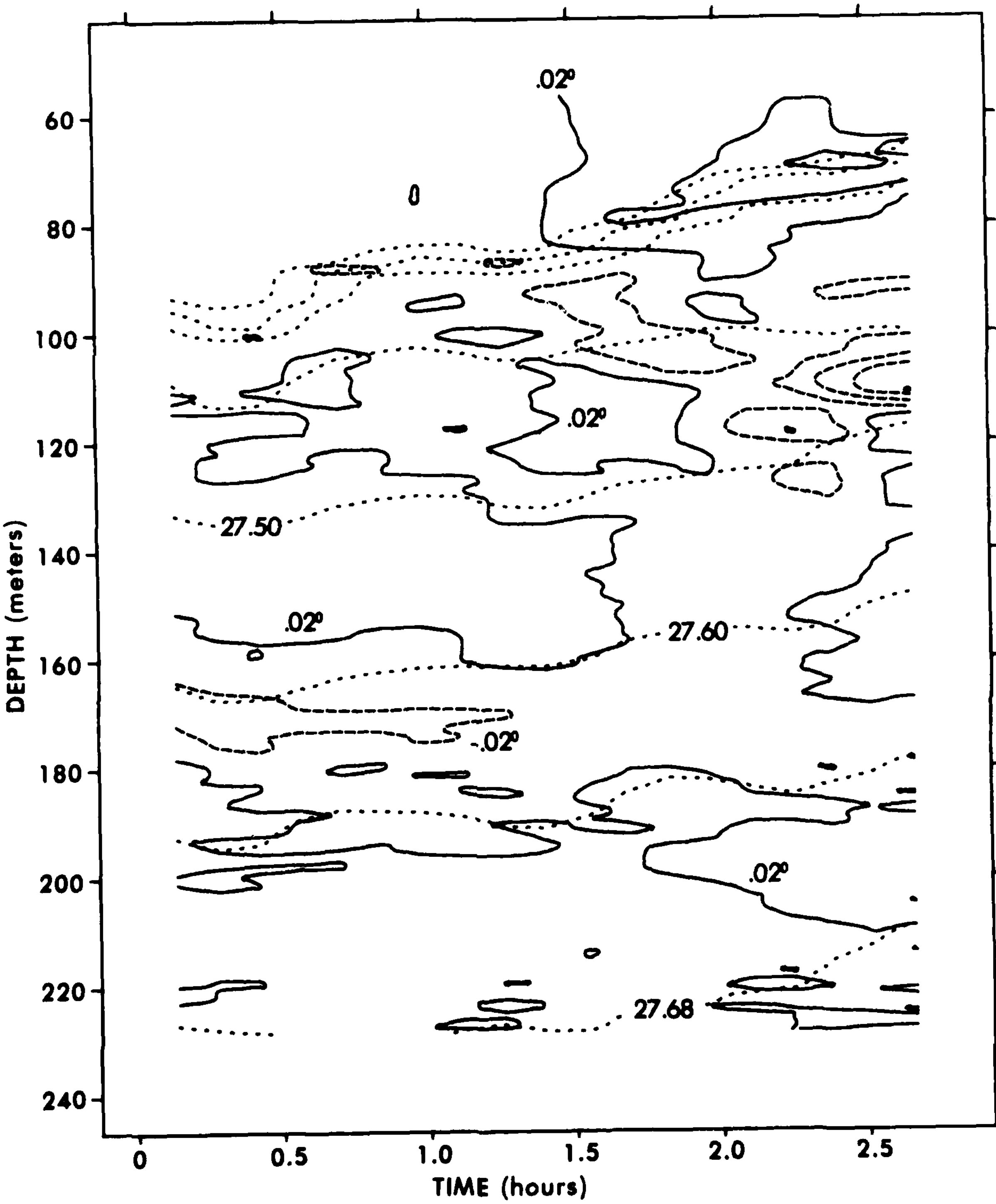

Figure 41. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 175161. (Contour interval for temperature is 0.04° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

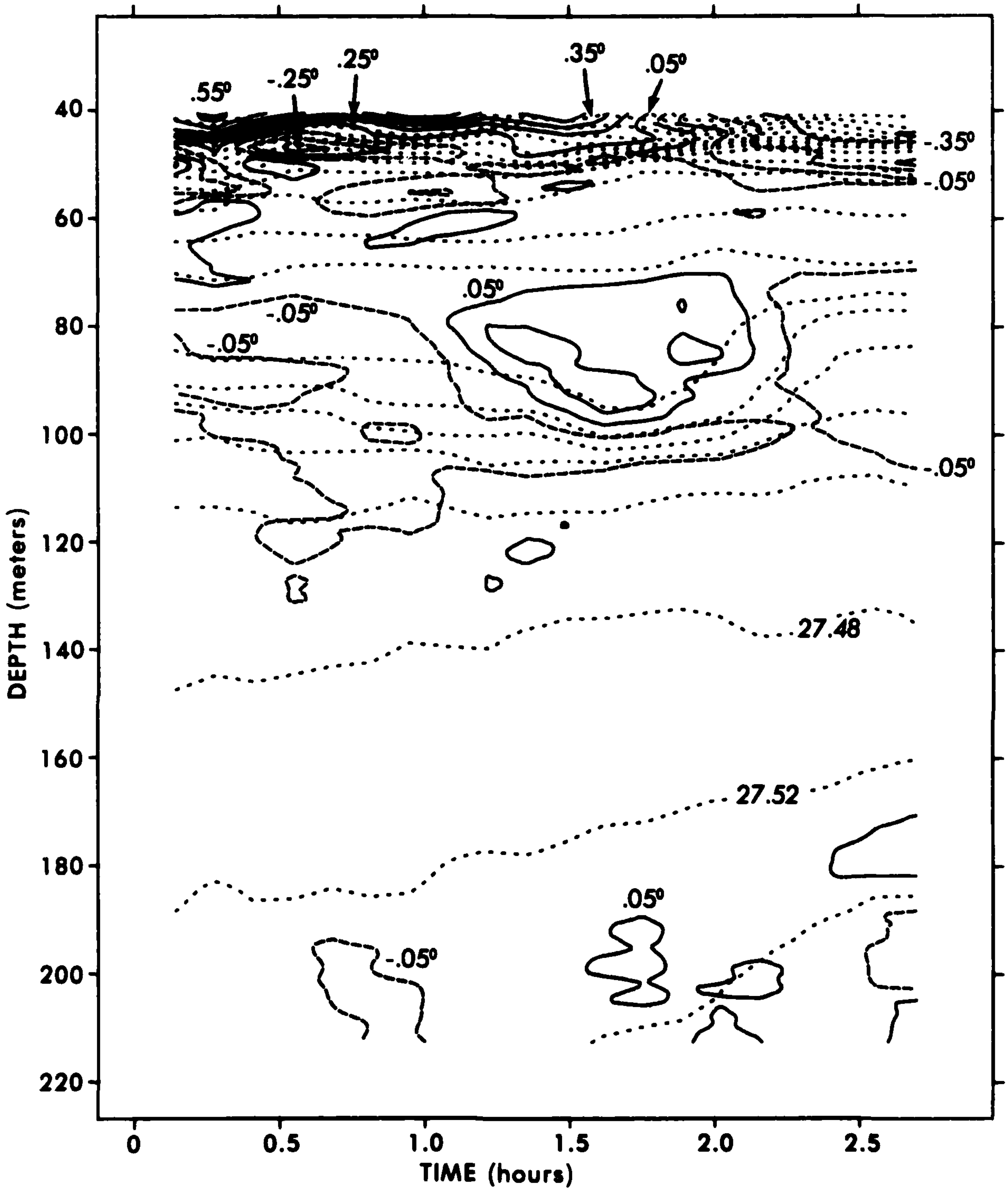

Figure 42. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 180168. (Contour interval for temperature is 0.1° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

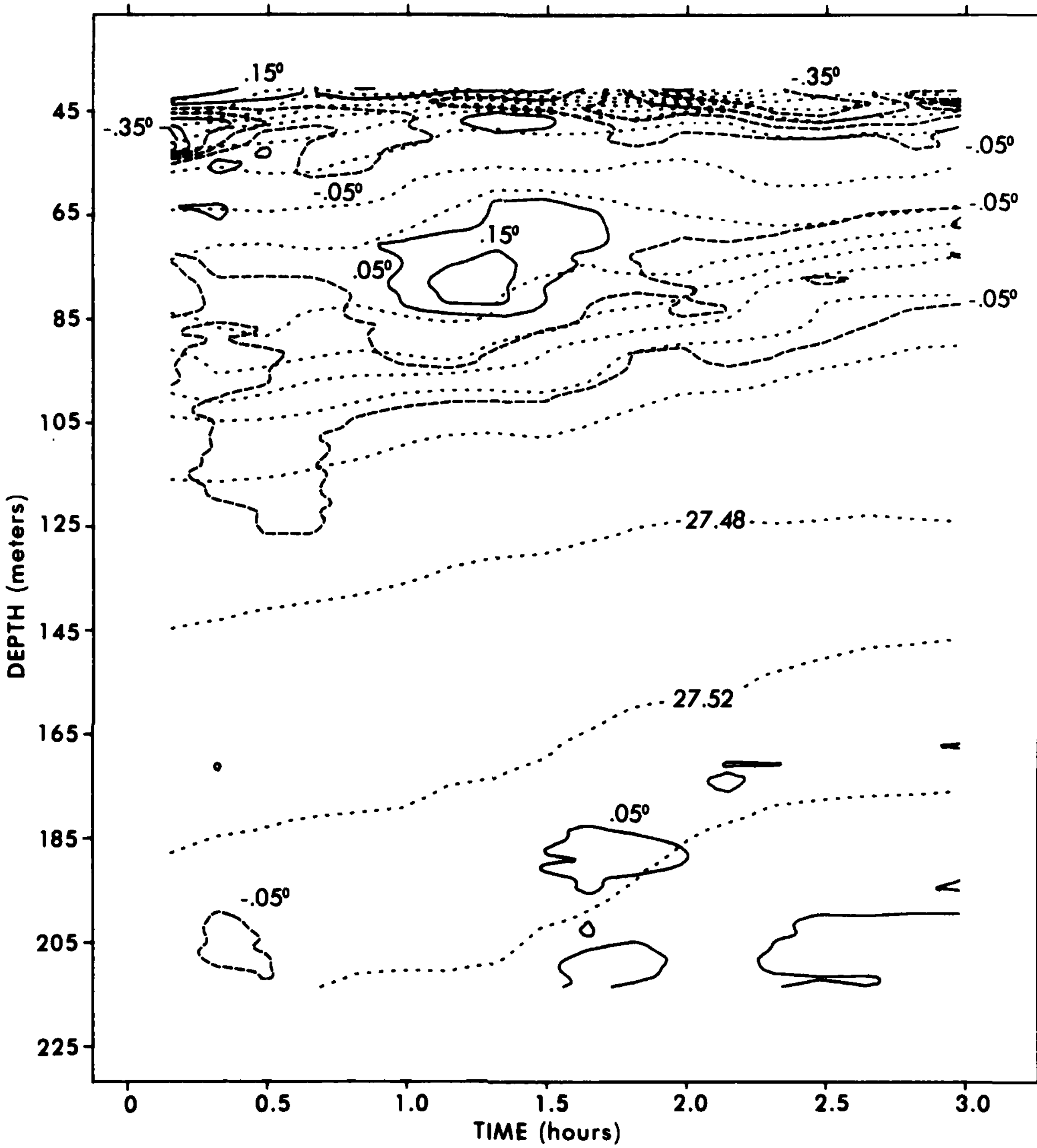

Figure 43. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 180169. (Contour interval for temperature is 0.1° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

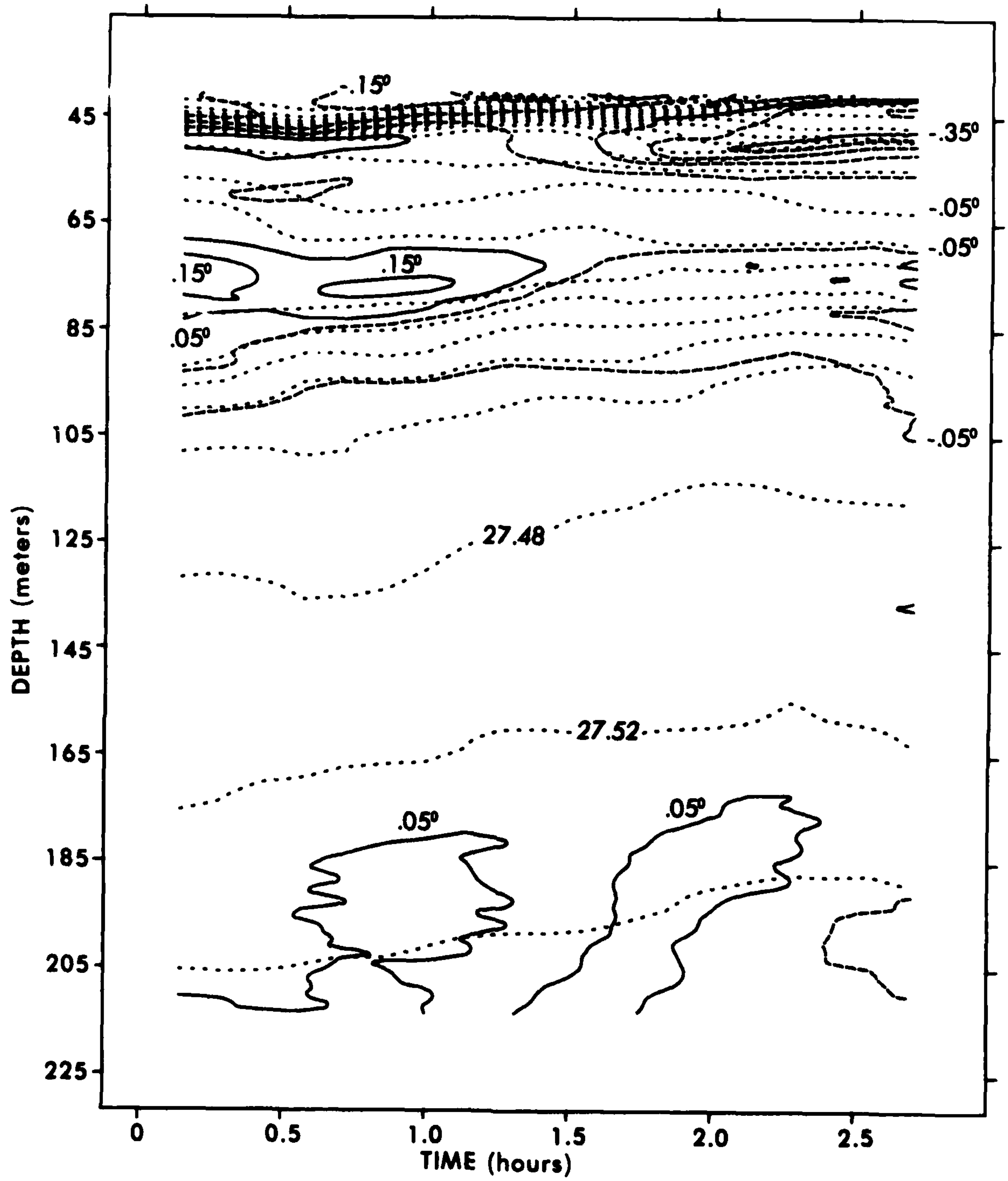

Figure 44. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 180170. (Contour interval for temperature is 0.1° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

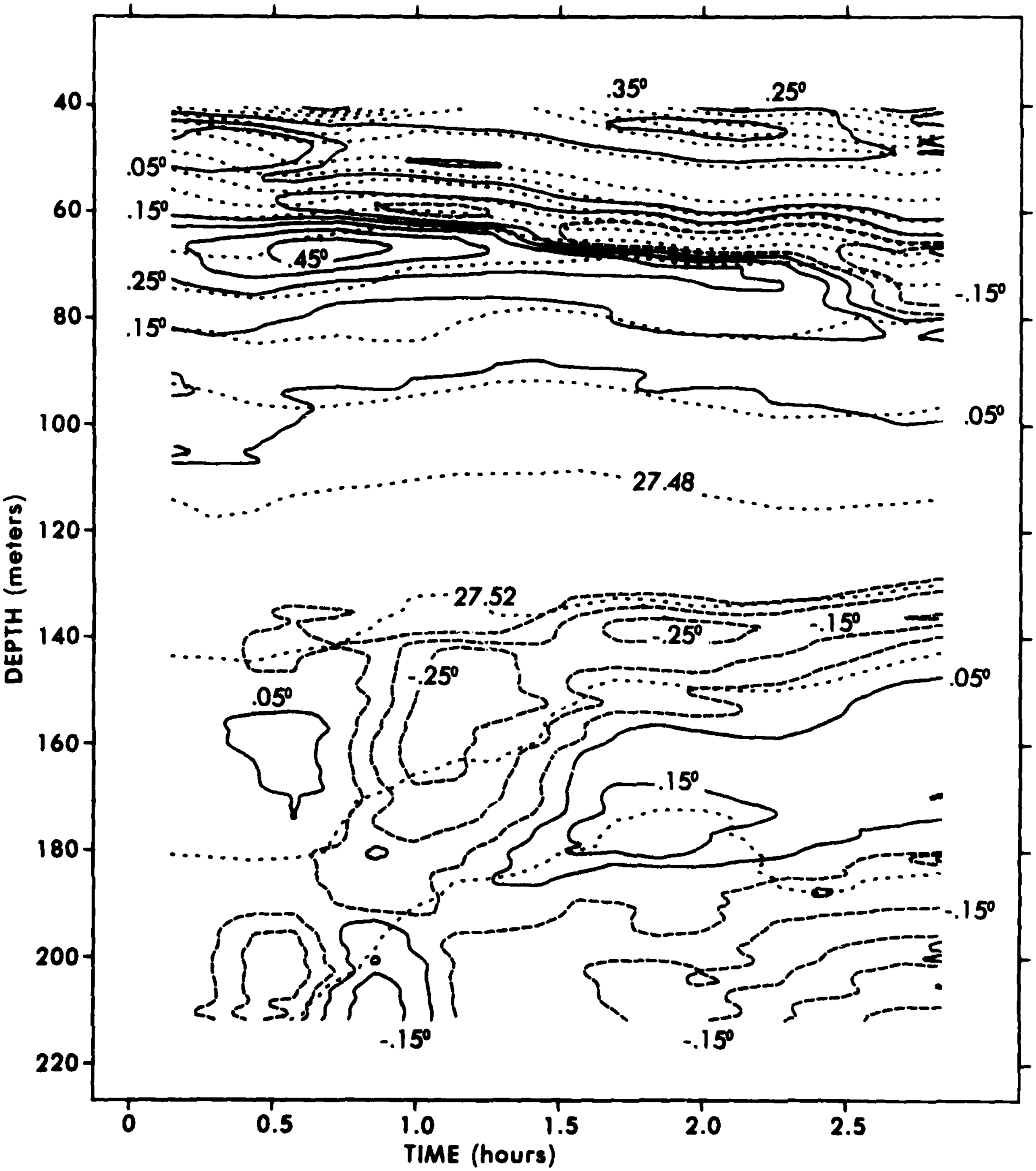

Figure 45. Isopycnal temperature anomalies and sigma-t for Norwegian Sea Station 180171. (Contour interval for temperature is 0.1° C; dashed contours are negative, solid are positive. Contour interval for sigma-t is 0.04; contours are dotted. Abscissa is time but can be interpreted as horizontal distance with about 1 km/hour.)

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Double Diffusion
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Norwegian Sea
Interleaving

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Isopycnal variability of temperature is examined for the upper ocean on scales of several meters in the vertical and several hundred meters in the horizontal. A considerable number of rapidly sampled CTD profiles obtained in the Sargasso Sea (1979) and in the vicinity of the Faeroe Islands north of Scotland (1980) are described. Analyses of finescale variability within, adjacent to, and away from a strong front are compared. A number of small, intense features are revealed which would likely have been missed by conventional sampling procedures.

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Analyses of strong interleaving in frontal regime supports the hypothesis that salt fingers drive thermohaline instrustions.

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